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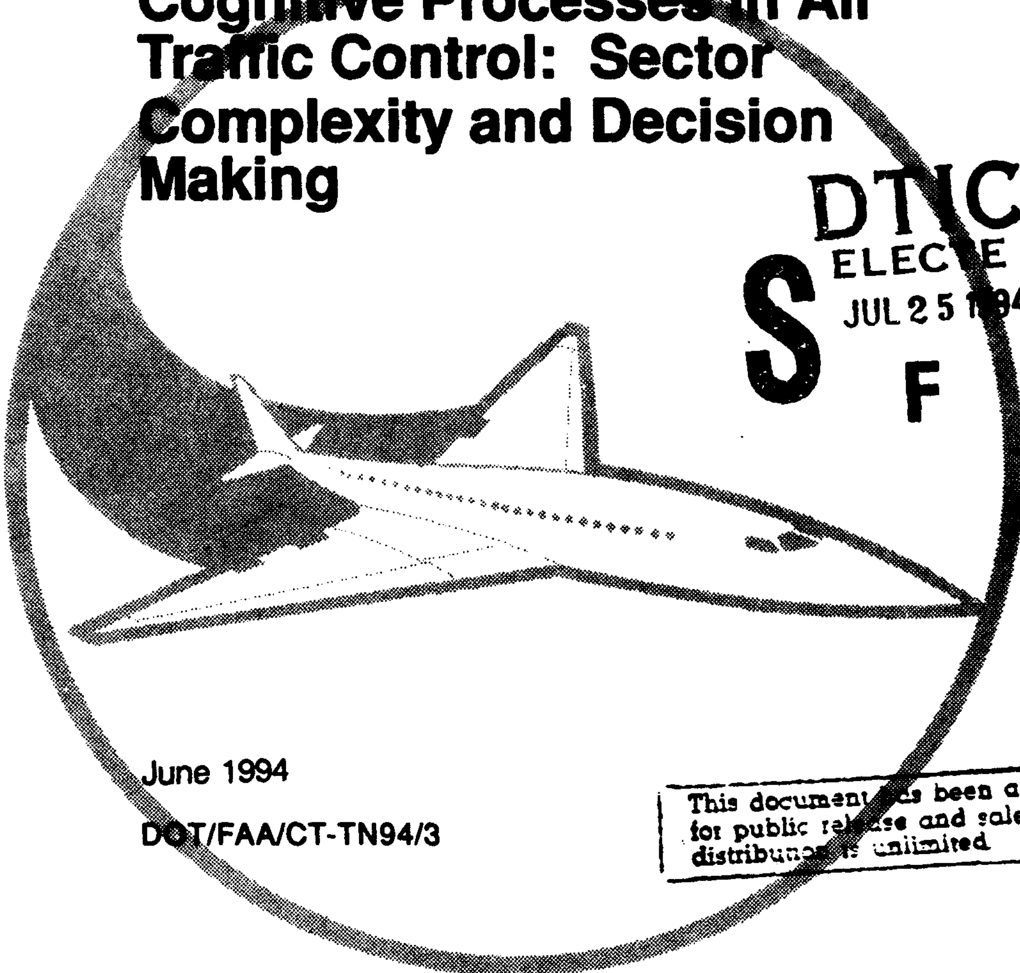
Application of Research Techniques for Documenting Cognitive Processes in Air Traffic Control: Sector Complexity and Decision Making



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16. Abstract

Air traffic controller decision making is a key contributor to safety in the National Airspace System (NAS). Little systematic attention has been paid, however, to investigating the parameters of controller decision making or the factors that affect decision making in the air traffic control (ATC) environment. Because controller decision making takes place within the context of controlled airspace, it is necessary to understand the elements of that context as potential influences on decision-making outcomes. Previous research was conducted on sector complexity in the Great Lakes Region. The research documented in this report was designed to further investigate the elements of en route sector complexity in the Southeast Region and to examine the effects of those elements on controller decision making.

Nineteen candidate factors were generated through the use of direct and indirect methods. Of these 19 factors, 11 had significant product-moment correlations, with overall ratings of sector complexity. The results suggested that the use of indirect approaches for knowledge elicitation did not prove to have any distinct advantage in terms of information yield over directly asking controllers for candidate complexity factors.

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EXECUTIVE SUMMARY

Air traffic controller decision making is a key contributor to safety in the National Airspace System (NAS). Insufficient systematic attention has been paid, however, to investigating the parameters of controller decision making, or the factors that affect decision making in the air traffic control (ATC) environment. Because controller decision making takes place within the context of the controlled airspace, it is necessary to understand the elements of that context as potential influences on decision-making outcomes. The research documented in this report was designed to investigate the elements of en route sector complexity in the Southeast Region, and to examine the effects of those elements on controller decision making.

Study of Sector Complexity.

Phase I of the research focused on collecting and analyzing data on sector complexity. The research took place at the Jacksonville Air Route Traffic Control Center (ARTCC) in Jacksonville, Florida. Two complementary methods were used: 1) direct elicitation of sector complexity factors and related data from Jacksonville personnel; and 2) indirect identification of sector complexity factors through the application of statistical procedures.

A preliminary study consisted of tests of data collection and analysis methods, and produced a list of 24 initial complexity factors for further study. The goals of the main study were to apply the data collection methods to a larger group of controllers, develop an initial set of complexity factors, and verify that a reduced set of these factors could adequately account for sector complexity. Analysis of the data from the main study identified a set of 19 Initial Factors that were used for further analysis. To complete Phase I, 11 Final Factors, that showed a significant relationship with sector complexity, were identified.

Other results of Phase I indicated that individual controllers may respond differently to given constellations of complexity factors. Comparison of the complexity factors, generated by the direct and indirect methods, suggested that the direct method can be used reliably to obtain information on sector complexity. Although the indirect method provides comparable information, the time spent in interpreting the results adds to the cost of the analysis.

A comparison was made between the ordering of Jacksonville sectors that emerged from participants' factor ratings, and the ordering from a previous annual review that used a Federal Aviation Administration (FAA) formula for determining sector complexity. Although the two orders were statistically related, the relationship was an extremely weak one. It is possible, therefore, that the FAA rating system may not adequately account for sector complexity. Further validation work is needed, however, to confirm

the improved effectiveness of the method for evaluating sector complexity developed by this study.

Study of Controller Decision Making.

Phase II of the study was designed to investigate controller decision making within the context of the sector environment. ATC simulation problems were developed to reflect sector complexities ranging from low to high. One problem was used in a preliminary study. Before working the problem, participants were asked to predict the ATC conflicts that would occur, to describe anticipated control actions along a timeline, and to predict the trajectories of aircraft in the problem. They also rated the problem on the sector complexity factors identified in Phase I.

Results for Phase II are related to several key categories of controller behavior: problem analysis, planning, problem solving, and acting. An interesting result for problem analysis is that participants did not agree on the anticipated number, or safety risk, of potential conflicts in the problem. Some participants predicted more conflicts than would have actually occurred, while some did not predict those that would have occurred.

The effectiveness of participants' planning activities was assessed by comparing their predictions to their actual actions. The effectiveness of the initial plan varied from 16 to 73 percent. Participants were able to draw the projected routes of aircraft through to the end of the problem and in general, planned flight paths closely resembled the actual routes taken.

Evidence was found for Recognition-Primed Decision Making (RPD), that is, controllers who were familiar with the sector and the problem, and recognized the problem and the solution. Most participants combined RPD with working out the details of the solution. This finding converges with other research on decision making that has been conducted in other problem domains (Klein, 1989).

The number of actions taken by the participants ranged from 21 to 32. Reasons for changes in the plan included unpredictable aircraft behavior, detection of conflicts, and changes in the sequencing method employed.

Analysis of the effects of sector complexity factors indicated a lack of agreement between the participants on some of the complexity scales. The highest rated complexity factors were all related to the theme of handling arrivals and departures. Complexity factors appeared to influence controllers in moving aircraft away from their original flight plans to achieve correct spacing, and to reduce the potential for conflict. Further research is recommended to validate these preliminary findings and to extend the investigation of controller decision making.

1. INTRODUCTION.

The purpose of this research was to document the cognitive foundations of air traffic control (ATC). The focus was on two components of cognitive processing in ATC: cognitive structures and decision-making strategies. The term cognitive structure refers to any organization of ATC-specific knowledge, for example, the controller's knowledge about ATC procedures, sector geography, flight characteristics, and previously-experienced air traffic situations. Cognitive structures are also known as knowledge structures, or conceptual structures. Because these structures are thought to guide decision making, they are the key underpinnings for any further investigation of controllers' cognitive processes.

Documentation of knowledge structures permits the investigation of their influence on decision-making strategies. A strategy is a goal-directed use of resources, over time, in response to a situation that calls for judgment and choice among options. Because cognitive structures and decision-making strategies are not readily observable, it was necessary to devise a research plan that would produce valid, reliable behavioral data on which to base inferences about internal processes.

An updated version of the first report in this series, "Review and Evaluation of Applied Research Techniques for Documenting Cognitive Processes in Air Traffic Control" (Mogford, Harwood, Murphy, and Roske-Hofstrand, 1992), reviewed methods and techniques for exploring cognitive structures and decision making in ATC. That report also recommended appropriate tools for research in the ATC environment. Suitable techniques include retrospective verbalization, structured probed interviews, video analysis, multidimensional scaling (MDS), and Pathfinder analysis.

The work described in the present paper made use of the recommended methods to explore ATC knowledge structures and decision-making strategies. Knowledge structures, relating to the ATC environment, were addressed first, using the assumption that they provide both a context and a basis for decision making.

Because the en route sector is the focus of the en route traffic situation, its features and constraints bound the options available to the controller. Given that sectors may be alike in some ways, yet widely different in others, it is not possible to describe, much less predict, controller decision-making performance unless sector complexity is taken into account.

Thus, the first phase of the study focused on an investigation of en route sector complexity, and the second phase took initial steps toward investigating the effects of sector complexity on ATC decision making in an en route environment.

1.1 SCOPE.

Under CTA, INCORPORATED's (CTA's) contract with the Federal Aviation Administration (FAA) Technical Center, this specific research task included two major activities:

a. Activity 1, Review and evaluation of techniques for documenting cognitive processes in ATC.

b. Activity 2, Measurement of structures and strategies.

Phase I - Measurement of controllers' cognitive structuring of knowledge about sector complexity.

Phase II - Measurement of decision making strategies in the context of findings about sector complexity.

Activity 2 research followed activity 1, which is documented by Mogford, et al., (1992). The participating ATC facility was the Jacksonville Air Route Traffic Control Center (ARTCC), located near Jacksonville, Florida.

1.2 DOCUMENT OVERVIEW.

Activity 2 research begins with Phase I, cognitive structures. First, a preliminary study is described that established the context for the research on sector complexity, and tested candidate research techniques. Some initial insight into controllers' concepts about sector complexity emerged.

An account of the main study follows with a more extensive exploration of controller knowledge about en route sectors. These efforts resulted in an initial list of sector complexity factors. The final stage of Phase I was to attempt to determine which of these factors was most related to overall sector complexity, as judged by a group of Traffic Management Unit (TMU) controllers.

Phase II research sought to establish a relationship between the findings regarding sector complexity, and decision making. A preliminary study was completed that examined a number of aspects of controller behavior, and made a start at linking decisions and actions to sector complexity. Recommendations are made for further research.

2. PHASE I - CONCEPTUAL STRUCTURES OF SECTOR COMPLEXITY.

2.1 BACKGROUND AND APPROACH.

When performing ATC tasks, a controller's area of concern is a well-defined volume of airspace called a sector. Each terminal area, or en route center, includes many contiguous sectors. A sample sector map from the Jacksonville ARTCC is shown in figure 1.

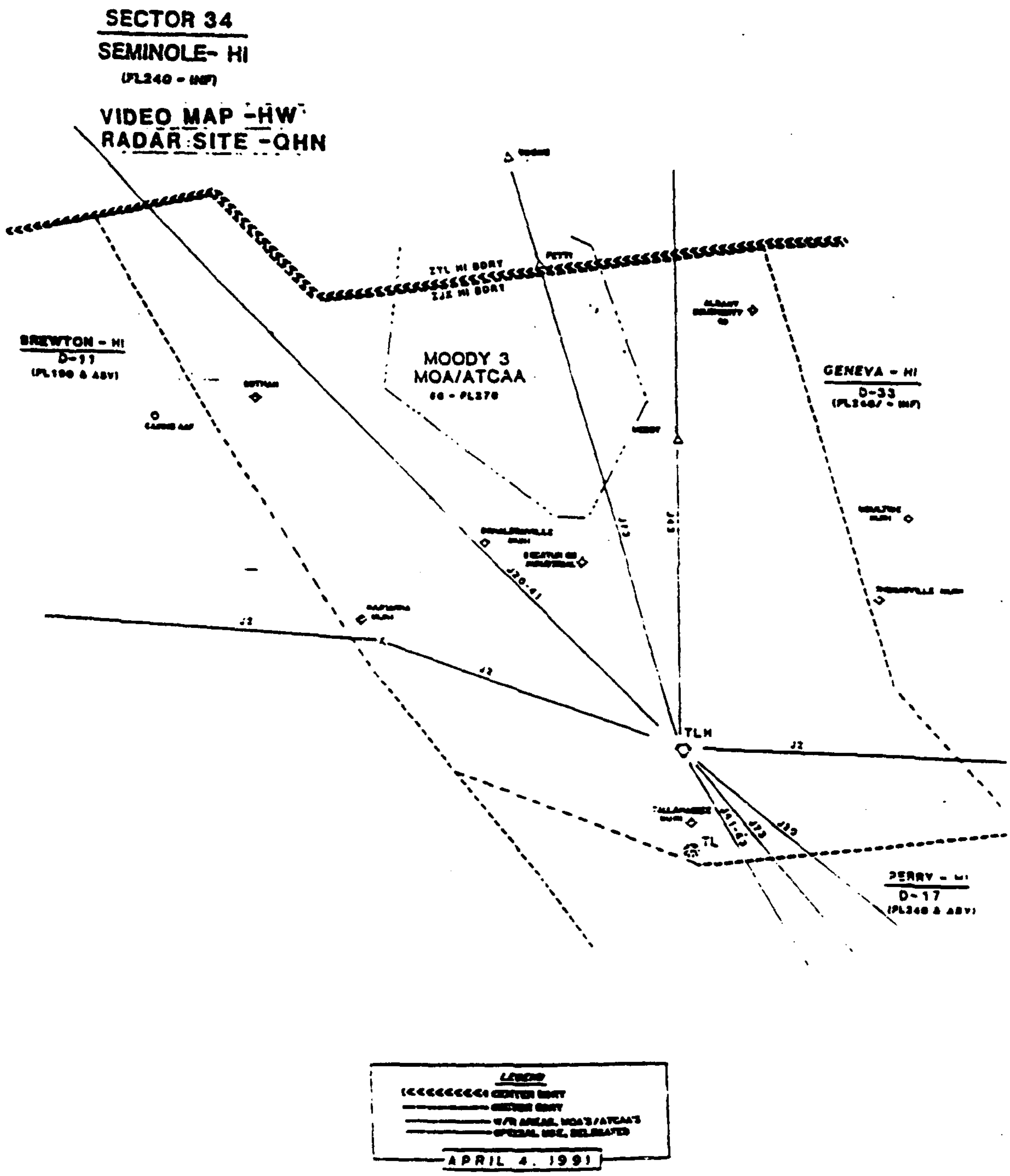

Figure 1. Sector Map for the Seminole Sector, Jacksonville, Florida ARTCC

Seminole sector is one of 38 sectors in the Center through which aircraft fly on their way to destinations in the United States and abroad.

The characteristics of a sector, in terms of airways, navigational aids, airports, traffic flow, weather, and other variables, define the controller's tasks and decisions. Examining the ways in which controllers structure their knowledge about sector complexity can establish the basis for further research on controller planning, problem solving, and decision making. The purpose of any such investigation is to disclose data and information about controller cognition that might help in improving ATC efficiency and effectiveness, e.g., through improvements in the design of sectors, planning and decision aids, information displays, and controller training.

As contributors to task demand, sector characteristics can be thought of as workload generators. Workload is the controller's subjective response to the "objective" conditions which create sector complexity. Stein (1985) found that global controller workload could be predicted by such factors as clustering/complexity of traffic patterns, frequency of handoffs outbound, number of flights handled, and frequency of handoffs inbound. However, the variables used by Stein did not focus on the direct contribution made to workload by sector characteristics (as opposed to traffic characteristics).

Hurst and Rose (1978) conducted a study to determine the principal behavioral stressors in the ATC environment. Four expert observers rated the level of degree of activity and behavioral arousal of controllers working 47 radar sectors in the Boston and New York areas. It was found that the activity and arousal measures were significantly related to peak traffic count and duration of radio communications. A multiple regression analysis showed that peak traffic alone accounted for 53 percent of the variance in activity and arousal. No other variable moderated this effect, including sector-related factors such as sector type and size. The authors stated that peak traffic may be the most potent and generalizable contributor to controller workload.

The FAA currently uses a formula to evaluate the complexity of en route airspace on a yearly basis. The procedure is described in FAA Order 7210.46, "Establishment and Validation of En Route Sectors." The formula consists of counts of the following activities, for a selected time period, at each en route center:

a. Departures.

b. Arrivals.

c. Radar vectored arrivals.

d. En route (requiring control functions).

e. En route (no control functions).

f. Emergencies.

g. Special flights.

h. Coordination (additional points when above functions require coordination).

There is some concern within the FAA, however, that this formula does not represent all of the important aspects of airspace complexity. In order to address this matter, Grossberg (1989) conducted research on sector complexity at the Chicago ARTCC. He defined complexity as "A construct, referring to the characteristics, dynamic and static, affecting the rate at which workload increases," and set out to define qualitative guidelines for limiting operational complexity. He noted that the FAA's standard sector complexity formula did not adequately account for the number of operational ATC errors occurring in the field.

Based on an earlier FAA study (Robertson, Grossberg, and Richards, 1979), Grossberg (1989) defined 12 candidate complexity factors:

a. Large sector airspace.
b. Small sector airspace.
c. Brief sector flight time.
d. Quick procedural adjustments.
e. Frequent coordination.
f. Complex control adjustments.
g. Complex flight paths.
h. Intersecting flight paths.
i. Climbing/descending flights.
j. Mix of aircraft types.
k. Frequency of holding/path stretching.
l. Heavy traffic.

Grossberg (1989) asked 97 ATC specialists and supervisors to rate each of the Chicago ARTCC sectors on the degree to which each factor increased sector difficulty or complexity. The factors cited most frequently were: control adjustments, such as merging, spacing, and speed changes; climbing and descending flight paths; and mix of aircraft types.

Finding that the factors could distinguish between sectors, Grossberg (1989) derived a "sector complexity index" by taking the most reliable, non-traffic related factors and calculating the mean of the highest four ratings for any given sector. For 27 of the

Chicago ARTCC sectors, he found that the resulting sector complexity ratings were highly correlated with the number of operational errors; as ratings increased, so did operational errors.

Grossberg's work on identifying salient complexity factors showed that the existing rating system was lacking in detail, and that improvements were possible. The work undertaken in Activity 2, Phase I, continued the research on sector complexity in order to identify additional factors, extend Grossberg's findings, test the selected knowledge exploration methods, and establish a basis for the study of controller decision making.

In Phase I, the previously identified knowledge exploration techniques (Mogford, et al., 1992) were classified into two general types, direct and indirect. Methods that rely on verbal reports, interviews, or simple questionnaires were considered direct approaches, and methods that involve a statistical analysis of controller judgments (including MDS and Pathfinder) were termed indirect approaches.

It is obvious why direct approaches would be part of any study that seeks to uncover controller knowledge about airspace characteristics. However, more needs to be said about the indirect approaches.

When experts are consulted to describe what they know about a particular domain, researchers are often concerned that a significant amount of expert knowledge is so well ingrained that it is not readily accessible for discussion. Experts automatically know how to accomplish a task, but may have difficulty describing all of the steps in the process, information used, decisions made, etc. Given this problem, an alternative is to observe or measure task-related behaviors that can provide insight into underlying knowledge structures. For this reason, indirect approaches, such as MDS and Pathfinder, have been developed.

MDS and Pathfinder are based on the assumption that if one wants to find out about the relationships between concepts or objects, a useful approach is to ask for similarity comparisons between them. Without preconceptions or external guidance, subject matter experts (SMEs) are asked to rate the similarity between pairs of concepts. Perhaps without fully being aware of it, they will use a set of criteria to accomplish this. In the case of en route sectors, they may compare them for traffic load, size of airspace, number of military flights, and other factors. Overall sector similarity will be judged on how close a given pair of sectors are on these dimensions.

Similarity judgments are also called distance judgments or proximity judgments, because they are estimates of how close (or how far apart) the objects being compared are on the concept of interest (in this case, complexity). MDS is useful because it can take similarity judgments between pairs of items as raw input and display a map, which spells out the relationships between the objects. It is then possible, by analyzing the pattern, to determine what characteristics or dimensions are being used by the SME in making the original comparisons.

For en route controllers, MDS can help uncover the complexity factors that are considered important when comparing different sectors. Pathfinder produces similar results, but shows more specific information about the linkages between concepts. (See appendix A for additional background information on MDS and Pathfinder.)

In Phase I, direct techniques for knowledge exploration included SME rankings of sectors by complexity, descriptions of complexity factors, ratings of sectors on complexity factors, and ratings of overall sector complexity. Indirect methods relied on collecting SME similarity judgments based on comparing sectors. In this case the researchers directed controllers to compare sectors specifically on their complexity. MDS could then be expected to help illustrate the sector characteristics that were being used by controllers to make the comparisons.

Phase I of the research, described in the current report, involved the application of both direct and indirect methods to derive and prioritize a set of airspace complexity factors. The work took place in two stages, item development, and factor selection. Item development resulted in a list of candidate sector complexity factors, and employed both direct and indirect approaches.

Once this had been accomplished, the list of factors was used to evaluate all of the sectors in the Center, and the resulting complexity ratings were analyzed for their ability to account for overall sector complexity. An additional goal was to determine the usefulness of each approach (direct and indirect) in generating salient factors (Mogford, Murphy, and Guttman, 1993).

2.2 PRELIMINARY STUDY.

The preliminary study of cognitive structures was intended to test the methodologies planned for the main study on controller knowledge about sector complexity. Two visits were made to the Jacksonville ARTCC to develop and evaluate the approach for the main study.

2.2.1 Participants.

The Jacksonville Airspace Procedures and Training Office personnel were extremely helpful in orienting the CTA research team to the Center's airspace and procedures. Six Airspace and Procedures Specialists (APSs) and four Full Performance Level (FPL) controllers from the West Specialization Area were recruited for the preliminary study. All six of the Center's APSs participated. FPL controller selection was not random, but was based on availability and scheduling requirements.

2.2.2 Materials and Apparatus.

Two data collection methods were developed and tested. These were structured interview techniques, and paired comparisons of airspace maps (which created data for MDS analysis). The West Specialization Area was used for the preliminary study. It is composed of seven sectors: Crestview, Waycross, Albany, Ashburn, Brewton, Tallahassee, and Nepta. (Although controllers use numerical identifiers for their sectors, the research team found it easier to employ the sector names.)

Response forms were designed to record data gained from structured interviews. An audio tape recorder was employed to capture narratives for later analysis.

Airspace maps were collected for all of the Jacksonville ARTCC sectors. In addition, photographs (showing traffic) were taken of the radar maps of all sectors. The maps, and enlargements of the photographs for the West Specialization Area, were attached to stiff cardboard backings, and placed on stands to serve as stimuli for the paired-comparison task.

FAA sector density and complexity ratings (from the most recent Jacksonville ARTCC Annual Center Review) were also collected.

2.2.3 Procedure.

Working in a group, but without discussion, the six APSs rated all 38 sectors in the Center for their own level of familiarity with each sector, the overall complexity of the sector, and the normal difficulty of controlling aircraft in the sector. They also listed important sector complexity factors. (Sector complexity was not defined as a term, but its meaning was left up to the judgment of the participant. The definition was left purposely open-ended so that all possible contributing factors could be identified.) All responses were recorded on forms designed for each task.

Each FPL was then interviewed separately and made responses on the appropriate forms. Participants ranked sectors on complexity, by sorting either photographs or maps of sectors into order of complexity. Each participant was given either photographs or maps (order was reversed for each subsequent participant), and asked to arrange them into a stack with the most complex sector uppermost. After completing this sorting task, the participant described the reasons for the rankings. This debriefing was tape recorded. Participants were then asked to list important complexity factors.

Finally, each FPL made judgments of the similarity in complexity between all possible pairs of sectors in the West Area using both photographs and maps. Either photographs or maps were used first (corresponding to the stimulus type used in the participant's first judgment task). Each possible pair of stimuli was placed on picture stands (small easels) in front of the participant, who recorded judgments of the two sectors' similarity in complexity on a special form.

2.3 RESULTS.

2.3.1 Familiarity, Complexity, and Difficulty.

The six APSs had been asked to rate all of the 38 Jacksonville ARTCC sectors for familiarity, complexity, and difficulty. It was discovered during data collection that each APS was familiar with a different set of sectors. When it came time to rate the 38 sectors for complexity and difficulty, it was not possible to collect a full set of judgments from each APS. Their lack of familiarity with some sectors resulted in several missing ratings in each case. The missing data were for different sectors for each APS. This made it impossible to correlate complexity and difficulty judgments for all sectors between the individual APSs.

It was possible, however, to average and correlate the available complexity and difficulty ratings across participants, and generate a complexity and difficulty rating for each sector. The product-moment correlation between ratings of complexity, and difficulty of the sectors was $r = .78$, $p<.01$.[1] This indicates that there was a high degree of relationship between the perceived complexity of a sector, and the judgment of how difficult it is to work.

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1 The Pearson Product-Moment Correlation Coefficient (r) is a statistical method of determining the degree of relationship between two sets of data (such as ratings of complexity and difficulty) about the same objects. The range of r is between zero (no relationship) and 1.0 (high relationship). The "p" value associated with the correlation indicates the probability that the correlation is the result of chance factors (in this case 1/100). The lower the p value, the higher the probability that the relationship is dependable and meaningful.

It was important, for the purpose of assessing complexity factors applying to all sectors, that a group of Jacksonville ARTCC personnel be familiar with a large proportion of the sectors in the Center's airspace. Given that the APSs had indicated familiarity with only some of the 38 sectors, they were asked to become acquainted with as many of their less familiar sectors as possible in preparation for the main study.

To supplement these APS findings, the knowledge of the TMU staff was also surveyed, with the expectation that some of them might be familiar with more of the Center's sectors. Of the 11 TMU personnel who responded, 4 claimed an average or higher familiarity with most of the sectors in the Center.

2.3.2 Sector Sorts.

During data collection, each of the four FPLs from the West Area ranked the seven sectors in this area by complexity. The Kendall correlation[2] between the four controllers was $\chi^2(6, N = 4) = 21.42$, $p = .0015$. Crestview was consistently chosen as the most complex sector. These results indicate a high degree of agreement between the controllers in the preliminary study, regarding the level of complexity of sectors within the West Specialization Area. They do not, however, explain why Crestview was considered to be the most complex sector.

2.3.3 Complexity Factor Lists.

As part of the test procedure, the six APSs, and four FPLs from the West Area, had been asked to list the factors they thought contributed to sector complexity. A total of 61 factors were collected. Discussions with the Jacksonville ARTCC training office permitted removal of redundant factors, and resulted in a list of 19 complexity factors. It was possible to rank most of the factors by counting how many times each was mentioned. Table 1 shows the factors and the number of votes each received.

The factors in table 1 were then combined with the 12 complexity factors defined in previous research on sector complexity by Grossberg (1989). Further redundancies were removed, resulting in a list of 24 Initial Factors. These were later evaluated for importance by the participants involved in the main study, and used to gather descriptive information on the Jacksonville ARTCC sectors to assist with subsequent MDS analyses. The list of the 24 factors is found in table 2.

2 The Kendall correlation coefficient is another measure of the degree of relationship, but is used to measure agreement between judges who have been asked to rank a set of people or objects. It ranges from zero (no agreement) to 1.0 (complete agreement). Unlike the Pearson correlation, it offers the ability to compute one measure of agreement between several judges.

Table 1. Factors Generated During the Preliminary Study and Frequency of Occurrence for the Four West Specialization Area Controllers

NO.	FACTOR NAME	OCCURRENCE
1.	RESTRICTED AREAS, WARNING AREAS, MOAS, AND NOTIFICATION TIME	8
2.	WEATHER	7
3.	AIRCRAFT MIX (COMMERCIAL, MILITARY, PRIVATE)	6
4.	CONVERGING/CROSSING TRAFFIC	6
5.	SECTOR BOUNDARIES/SECTOR SIZE	4
6.	CLIMBING/DESCENDING TRAFFIC HEAD-ON	4
7.	VOLUME OF TRAFFIC	4
8.	COORDINATION	3
9.	PERSONALITY OF FELLOW CONTROLLERS	3
10.	LACK OF RADAR AND RADIO COVERAGE	3
11.	MULTIPLE FUNCTIONS APPROACH CONTROL, TERMINAL FEEDER, EN ROUTE IN TRAIL SPACING, ETC.	3
12.	NUMBER OF FACILITIES TO DEAL WITH (SECTORS, CENTERS, APPROACH CONTROL, MILITARY)	2
13.	DEPARTURE AND ARRIVAL TRANSITIONS (STARS/SIDS)	2
14.	DEPARTING AND ARRIVING AIRCRAFT	1
15.	MILITARY REQUIREMENTS CONTRARY TO NORMAL FLOWS	1
16.	AIRLINE HUBBING	1
17.	IRREGULAR ALTITUDE STRATIFICATION	1
18.	EQUIPMENT	1
19.	FREQUENCY CONGESTION	1

Table 2. Initial Complexity Factors as Suggested by APS Staff and West Area FPLs in the Preliminary Study. (Factors are not listed in order of importance).

1.	NUMBER OF RESTRICTED AREAS, WARNING AREAS, MOAS, AND NOTIFICATION TIME
2.	FREQUENCY OF PROBLEM WEATHER
3.	MIX OF AIRCRAFT TYPES (COMMERCIAL, MILITARY, PRIVATE)
4.	NUMBER OF INTERSECTING FLIGHT PATHS
5.	PROBLEMS WITH SECTOR BOUNDARIES
6.	SIZE OF SECTOR AIRSPACE
7.	NUMBER OF CLIMBING/DESCENDING FLIGHTS
8.	AMOUNT OF HEAVY TRAFFIC
9.	FREQUENT COORDINATION
10.	ADEQUACY OF RADAR (AND RADIO) COVERAGE
11.	MULTIPLE FUNCTIONS (APPROACH CONTROL, TERMINAL FEEDER, EN ROUTE IN TRAIL SPACING, ETC.)
12.	NUMBER OF FACILITIES TO DEAL WITH (SECTORS, CENTERS, APPROACH CONTROL, MILITARY)
13.	NUMBER OF DEPARTURE AND ARRIVAL TRANSITIONS (STARS/SIDS)
14.	NUMBER OF DEPARTING AND ARRIVING AIRCRAFT
15.	FREQUENCY OF MILITARY REQUIREMENTS CONTRARY TO NORMAL FLOWS
16.	AMOUNT OF AIRLINE HUBBING
17.	IRREGULAR ALTITUDE STRATIFICATION
18.	ADEQUACY OF EQUIPMENT
19.	AMOUNT OF RADIO FREQUENCY CONGESTION
20.	BRIEF SECTOR FLIGHT TIME
21.	FREQUENCY OF PROCEDURAL ADJUSTMENTS
22.	FREQUENCY OF COMPLEX CONTROL ADJUSTMENTS (MERGING, SPACING, SPEED, ...)
23.	COMPLEX FLIGHT PATHS
24.	FREQUENT HOLD/PATH STRETCHING

2.3.4 Complexity Similarity Ratings.

2.3.4.1 Correlations between Judgments.

During data collection, the four FPLs had made complexity similarity ratings between the seven sectors in the West Specialization Area. (This was for the purpose of testing the MDS approach to developing complexity factors.) When Kendall correlations were calculated between the judgments of the four West Area FPLs for photographs and maps, it appeared that the group was generally in agreement about the similarity in complexity of the sectors. The result for photographs was $\chi^2(20, N = 4) = 43.78$, $p = .0016$, and for maps it was $\chi^2(20, N = 4) = 43.20$, $p = .0019$.

The researchers were interested in the differences between using radar screen photographs, as opposed to sector maps, for collecting judgments about sectors. When product-moment correlations between each individual's complexity similarity judgments, using photographs and maps, were computed, results ranged from 0.78 to 0.94 (all significant at $p < .01$). The Kendall correlation between all judgments of photographs and maps was $\chi^2(20, N = 8) = 85.01$, $p = .0000$. These results show that there was not much difference in complexity similarity ratings when participants based their ratings on photographs with traffic, as opposed to sector maps without traffic.

When asked for an opinion on which stimuli to use in the main study, the FPLs said they preferred screen photographs, while the APSs selected sector maps. Each group chose the medium they worked with most of the time. Since results for photographs and maps were virtually interchangeable, use of either photos or maps would have been valid. Due to technical difficulties in collecting a complete set of radar screen photographs, sector maps were chosen for subsequent data collection efforts.

2.3.4.2 MDS.

To further explore the data from the preliminary study, an MDS analysis was conducted on the sector complexity similarity data sets collected, using photographs and maps. The purpose of this analysis was to examine the effectiveness of MDS as an indirect knowledge-exploration tool.

The proximity data (i.e., the ratings of paired sectors for similarity in complexity) were analyzed, using an MDS procedure known as INDSCAL, a subroutine of alternating least squares scaling (ALSCAL) in the Statistical Package for the Social Sciences (SPSS). INDSCAL combines sets of proximity measures for a group of participants, and creates a shared stimulus space. Using this space, it is possible to analyze the relationships between a set of objects, such as sectors.

INDSCAL computes how efficiently it has accounted for each participant's proximity data in the shared space, and also calculates a weight space, which shows to what degree each participant emphasizes the common MDS dimensions. The goodness of fit of the solution or effectiveness is measured by minimizing stress[3] and maximizing the amount of variance (or information) accounted for R^2.[4]

Similar two-dimensional MDS stimulus spaces resulted for photos and maps, and only the maps data were analyzed further. The result for the maps data (shown in figure 2) achieved a stress of .13 and accounted for 91 percent of the variance in the data. The MDS space for the maps was interpreted by the experimenters using sector information obtained at Jacksonville's ARTCC with the assistance of the Center's training staff. One dimension of the MDS space was related to sector traffic volume and the amount of military traffic, while the second dimension was concerned with traffic movement (such as altitude, overflights vs. departures/arrivals, and number of procedures). For the four West Area FPLs, these appeared to be the underlying factors guiding their complexity comparisons of the seven sectors.

Each participant's complexity-similarity judgments were well accounted for in the combined MDS space, but there was an indication that they each used the underlying complexity dimensions differently when making their judgments. Figure 3 shows the weight space for the four FPLs, and indicates how much each participant emphasized each dimension when judging the similarity of complexity between pairs of sectors.[5]

2.3.4.3 Pathfinder.

Pathfinder analysis was considered as another way to explore the structure of the sector complexity information. The Pathfinder algorithm generates a family of link-weighted networks from a set of distance data (see appendix A). A derived Pathfinder network consists of a set of concepts and links that directly connect pairs of highly-related concepts. This network represents the basic organization of existing knowledge structures or elements based on an individual's experience.

---

3 Stress is the square root of a normalized residual sum of squares and should be below 3.0 in a well-fitting MDS solution.

4 R^2 ranges from zero to 100 percent. MDS results that produce an R^2 of over 75 percent are considered acceptable.

5 If subjects used each dimension about equally, they would lie on a diagonal passing through the zero point on the weight space graph. Deviation from the diagonal indicates a preference for one dimension or the other. Distance from zero on either dimension indicates the degree of emphasis on that dimension.

```
     DERIVED STIMULUS CONFIGURATION:
     DIMENSION 1 (HORIZONTAL) VS DIMENSION 2 (VERTICAL)
    -+----+----+----+----+----+----+----+----+----+----+-
     :                         :                         :   High Volume
 2.1 -+                        :                         +   More Military
     :                         :                         :   Traffic
     :                         :                         :
     :                         :CREST                    :
     :                         :                         :
     :                         :                         :
 1.0 -+                        :                         +
     :                         :                         :
     :                         :                         :
     :               BREW      :    WAY  ALBY            :
     :                         :                         :
     :                         :                         :
 0.0 -+--------------------------------------------------+
     :                         :                         :
     :                         :                         :
     :                         :  ASH                    :
     :                         :                         :
     :                         :                         :
-1.0 -+                        :                         +
     :   NEPTA                 :                         :
     :                         TALL                      :
     :                         :                         :
     :                         :                         :
     :                         :                         :   Low Volume
-2.1 -+                        :                         +   Less Military
     :                         :                         :   Traffic
    -+----+----+----+----+----+----+----+----+----+----+-
   -2.5      -1.5      -0.5       0.5       1.5       2.5

    High Altitude                          Low Altitude
    Overflights                    Departures/Arrivals
    Fewer Procedures                   More Procedures
```

Figure 2. INDSCAL Space for the Four West Area FPLs in the Preliminary Study

```
      DERIVED PARTICIPANT WEIGHTS:
      DIMENSION  1  (HORIZONTAL)  VS  DIMENSION  2  (VERTICAL)
    -+----+----+----+----+----+----+----+----+----+----+-
0.9 -+       2                                         +
     :                                                 :
     :                                                 :
     :                                                 :
     :                                                 :
     :                                                 :
0.7 -+                                                 +
     :                                                 :
     :                              1                  :
     :                                                 :
     :                                                 :
     :                                                 :
0.5 -+                                                 +
     :                                          4      :
     :                                                 :
     :                                                 :
     :                                                 :
     :                                                 :
0.3 -+                                                 +
     :                                                 :
     :                                                 :
     :                                                 :
     :                                                 :
     :                                                 :
0.1 -+                                              3  +
     :                                                 :
     :                                                 :
    -+----+----+----+----+----+----+----+----+----+----+-
    0.0       0.2       0.4       0.6       0.8       1.0
```

Figure 3. Weight Space for the Four West Area FPLs in the Preliminary Study

Pathfinder analysis was applied to the averaged similarity judgment matrices for maps rated by the West Area controllers in the preliminary study, as shown in figure 4. The complexity factors were identified that appeared to be the basis for links between sectors. These factors proved to be similar to those derived from the MDS results. Based on this finding, and the large amount of time required to interpret each Pathfinder graph, it was decided that Pathfinder analysis of the sector proximity data would probably not offer significantly more information than MDS. Therefore, Pathfinder was reserved for the analysis of the complexity factors identified through the direct and indirect methods. This Pathfinder analysis is discussed in section 2.9.3.

2.4 MAIN STUDY.

Methods and materials used in the main study were selected on the basis of outcomes of the preliminary study. To develop a list of Candidate Factors, the CTA research team made a third visit to the Jacksonville ARTCC. Both direct (questionnaire) and indirect (similarity judgments) approaches were used to collect data on sector complexity on a larger scale.

2.4.1 Participants.

A total of 30 controllers (25 FPLs and 5 trainees or Developmentals) were involved in the main study: 5 from each specialization area. Other participants included 5 controller trainees, 3 TMU staff, and 3 APSs. The 41 participants were all volunteers, and were selected on the basis of availability during the time period of the data collection visit.

Each FPL's primary familiarity was with the seven to nine sectors within a specialization area. Some specialization areas were composed of sectors of mainly one type, such as high or low altitude. Airspace Procedures and TMU participants were selected on the basis of their familiarity with the sectors in the Center (as previously tested by questionnaire), as well as their availability on the days planned for the study.

2.4.2 Materials and Apparatus.

Tools for data collection included both computerized and paper-based methods. A Macintosh Hypercard program (called the "Judgment Recorder") was developed for the collection of complexity comparison judgments. Given that the participants in the preliminary study made similar responses to both maps and photographs of Jacksonville sectors, it was decided to use maps as stimuli, since they were readily available. Sector maps were scanned and digitized using a Hewlett-Packard scanner. They were then converted to Macintosh "PICT" format, and incorporated into the Judgment Recorder.

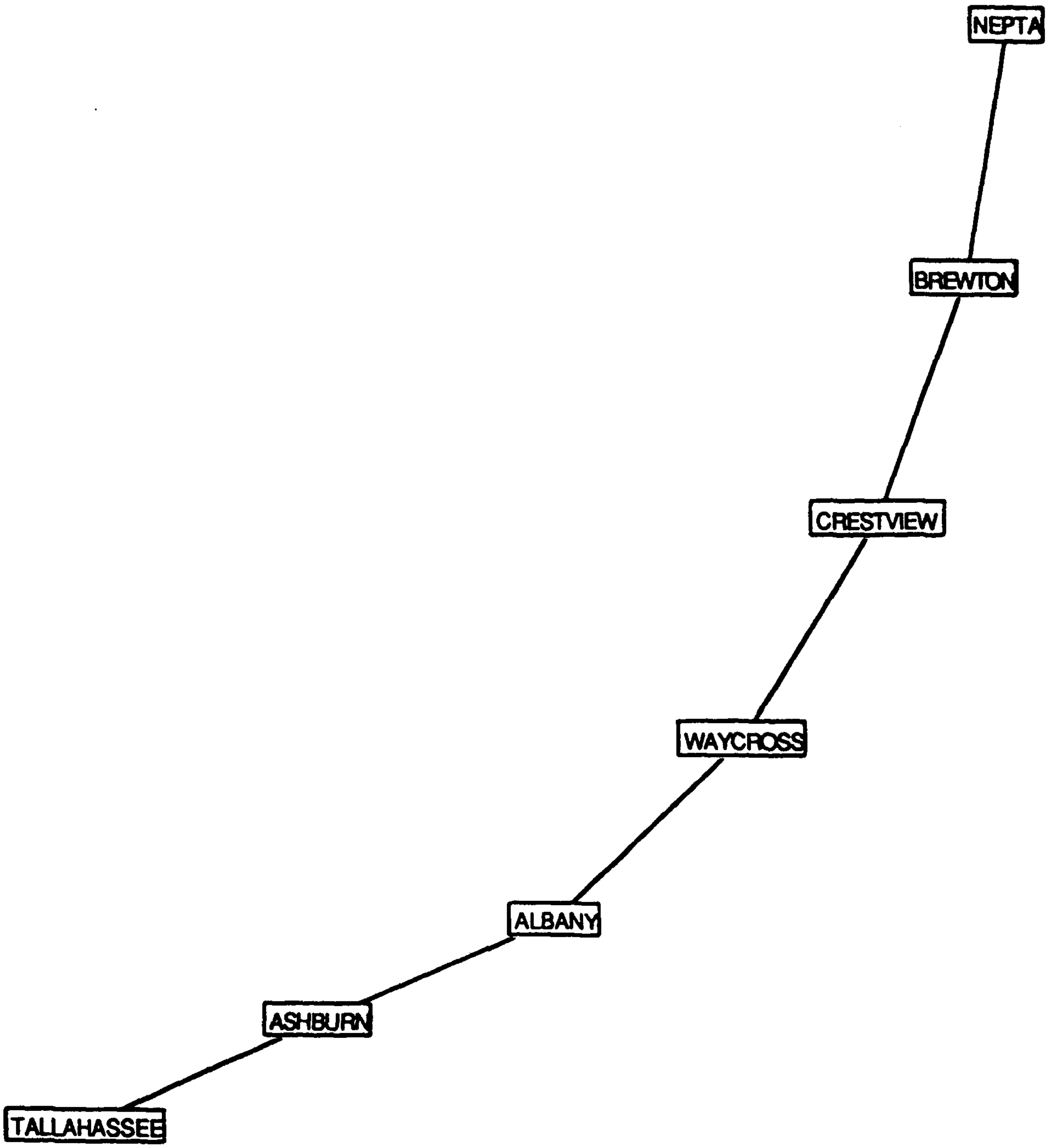

Figure 4. Pathfinder Results for West Specialization Area

The stimuli were presented on 21-inch, high-resolution color monitors connected to a Macintosh IIci or IIcs system. Participants made responses by moving a mouse-controlled pointer, which controlled stimulus presentation, and selection of complexity similarity values on an on-screen scale.

The study also employed several paper questionnaires, including the following forms (not all forms were used with all participants):

a. Request for a listing of complexity factors.

b. Order of sorting sectors for complexity.

c. Ratings of sectors on 24 previously compiled complexity factors (derived from the preliminary study and previous work by Grossberg (1989)).

d. Importance ratings for 24 complexity factors.

e. Word-Shape Sorting Test (WSST) (a test of cognitive style).

2.4.3 Procedure.

The computerized Judgment Recorder was used to present sector maps to 25 FPLs, 5 trainees, 3 APSs, and 3 TMU staff members. Upon arriving at the room used for the main study, participants filled out a form with their name, age, sex, and years of experience. They were then introduced to the computerized Judgment Recorder and completed a tutorial. Following this, the FPLs from the North, South, East, West, or Central Specialization Areas, and Developmentals from the East Area, first rated their familiarity with the seven to nine sectors in each area. They then made complexity similarity comparisons between all possible pairs of sectors.

The Airspace Procedures and TMU personnel completed the same procedure, but did not compare all possible pairs. After a participant had made a rating of familiarity with each sector, it was possible to exclude all sectors that were not well known. For each participant, the experimenters evaluated the proportion of the total number of sectors that fell within each level of familiarity on a seven-point scale. Each participant employed the scale somewhat differently, and a cutoff was selected in each case, which resulted in about 10 percent of the least familiar sectors being excluded from the paired comparisons. As a result, the Airspace Procedures and TMU participants rated from 24 to 36 of the 38 sectors. Although this required hundreds of paired comparisons, participants were encouraged to respond rapidly without excessive deliberation, and an entire comparison session required no more than 90 minutes.

Sector maps were presented without air traffic. It was assumed that, although traffic load, aircraft routes, and aircraft characteristics might play a part in complexity, having traffic on the sector maps would be misleading and possibly confounding. The presence of specific aircraft targets could have encouraged participants to compare sectors based on the number of aircraft, and the existence of, or potential for, conflicts. It also would have been nearly impossible to select representative and comparable samples of traffic and ATC situations for each sector.

All participants were asked to list the factors that they thought contributed to sector complexity, and to complete the WSST. FPLs and Developmentals also sorted sector maps within their specialization areas by level of complexity, and described how they determined the order. They also completed two rating forms. These forms employed an initial set of 24 complexity factors compiled from the preliminary study and work by Grossberg (1989). All of the factors were evaluated for importance (on a 7-point scale), and every sector in each specialization area was rated on all 24 factors (on 7-point scales).

2.5 Results.

The results consisted of several different sets of data rating sector complexity. Some data had been collected using direct methods, and some using indirect measures. Each type of information was considered separately, and then combined, in an attempt to identify important complexity factors for the Jacksonville ARTCC airspace.

2.5.1 Sector Sorts.

The five controllers within each specialization area had sorted the sectors within their area by level of complexity. Kendall correlations were calculated for each area, as shown in table 3. This statistic indicated the degree of agreement between the five FPLs or Developmentals in each specialization area. The final line in table 3 shows the amount of agreement between the East FPLs and Developmentals. In every case, there was a significant level of agreement, suggesting that the participants sorted the sectors by complexity in similar ways.

Table 3. Kendall Coefficient of Concordance for Each Specialization Area, Developmentals, and all East Controllers

AREA	W	CHI^2	df	SIGNIFICANCE
NORTH	.68	23.71	7	.0013
SOUTH	.64	19.29	6	.0037
EAST	.77	27.07	7	.0003
WEST	.84	25.04	6	.0003
CENTRAL	.79	23.66	6	.0006
DEVELOPMENTAL	.64	22.4	7	.0022
ALL EAST	.67	46.67	7	.0000

The following sectors were judged most complex in each Specialization Area:

AREA	SECTOR
North	Brunswick
South	St. Augustine St. Johns (tied)
East	Aiken
West	Crestview
Central	Seminole
East (Developmentals)	Aiken

2.5.2 Complexity Factor Lists.

All FPLs were asked to list the complexity factors they thought were most important in evaluating Jacksonville ARTCC sectors. This resulted in over 200 factors. The lists were combined and redundancies were removed. Table 4 shows the resulting shortened list of factors, with the accompanying frequency and percentage of occurrence of each factor. Developmentals were excluded, because it was found that much of their data diverged from that of the FPLs. This was probably due to their relative lack of experience.

2.5.3 Complexity Factor Importance.

Participants had also rated the importance of the 24 Initial Factors, in order to determine which were most salient. Developmentals were again excluded from the combined data set, due to their relatively limited amount of ATC knowledge. (It was noted that eliminating their scores from the data substantially reduced the variability in the ratings for each factor.) A mean importance rating was calculated for each factor. Table 5 shows the factors arranged in order of average importance.

Table 4. Factors Listed, Number of Times Mentioned, and Percent of Possible Responses by FPLs During Main Study

FACTOR	FREQUENCY	PERCENT
COMPLEX FLIGHT PATHS	30	14.0
RESTRICTED AREAS, WARNINGS, MOA	22	5.5
SIZE AIRSPACE	21	5.6
TRAFFIC VOLUME	18	5.0
WEATHER	16	4.7
ARRIVAL/DEPARTURE SEQUENCING/SPACING	15	4.6
COORDINATION	15	4.9
MILITARY TRAFFIC	14	4.8
AIRCRAFT MIX	13	4.7
SECTOR BOUNDARIES	13	4.9
FLOW RESTRICTIONS	10	4.0
TRANSITIONING	9	3.7
CLIMBING/DESCENDING FLIGHTS	6	2.6
DEPARTING/ARRIVING AIRCRAFT	3	1.3
EQUIPMENT	3	1.3
FREQUENCY CONGESTION	2	0.9
IRREGULAR ALTITUDE STRATIFICATION	2	0.9
VFR/IFR	2	0.9
MULTIPLE FUNCTIONS	1	0.5

Table 5. Average Importance Ratings for 24 Complexity Factors

COMPLEXITY FACTOR	AVERAGE RATING
CLIMB/DESCEND FLTS.	6.3
RESTRICTED AREAS	6.2
WEATHER	6.0
NO. FACILITIES	5.9
COORDINATION	5.8
RADAR/RADIO COVERAGE	5.6
NO. DEP/ARR AIRCRAFT	5.5
AIRCRAFT MIX	5.4
MULTIPLE FUNCTIONS	5.4
RADIO CONGESTION	5.1
INTERSECTING FLIGHT PATHS	5.0
COMPLEX CONTROL ADJ.	5.0
ADEQUACY OF EQUIP.	5.0
TRAFFIC DENSITY	4.8
FREQ. MIL. REQS.	4.7
STARS/SIDS	4.5
COMPLEX FLT. PATHS	4.5
AIRLINE HUBBING	4.5
SECTOR BOUNDARIES	4.5
SIZE AIRSPACE	4.3
FREQUENT HOLDS/STRETCHING	3.9
FREQ. PROC. ADJ.	3.9
IRREG. ALT. STRAT.	3.2
SECTOR FLIGHT TIME	3.1

The Kendall correlation for FPL factor importance ratings was $\chi^2(23, N = 24) = 146.83$, $p = .0000$. This suggests that, although participants were from different specialization areas, there was a high degree of agreement among them about the importance of the initial set of complexity factors. Controllers from separate areas appeared to share similar viewpoints regarding complexity.

2.5.4 Sector Ratings.

FPLs rated sectors within each specialization area on each of 24 Initial Factors, compiled during the preliminary study. These ratings were used when interpreting MDS and Pathfinder data. Product-moment correlations were calculated within each specialization area to check on the agreement between participant ratings. All correlations were significant at $p < .01$.

Data for all 5 specialization areas were combined, and average ratings on each of the 24 factors were computed across participants for all 38 sectors in the Jacksonville ARTCC. (This resulted in each sector having ratings on each of the 24 factors.) Developmentals' data were excluded from this analysis under the assumption that their level of knowledge was not comparable with the FPLs' knowledge.

A weighted rating score for each sector was calculated by multiplying the rating of each sector on each of the 24 factors by the average importance assigned to that factor, and summing across all 24 factors for each sector. (For each sector: factor 1 rating X importance rating of factor 1 plus factor 2 rating X importance rating of factor 2, etc.) The resulting list is shown in table 6.

This list also includes the original set of FAA complexity ratings from the 1991 Annual Review of Jacksonville ARTCC Sectors. A comparison of the order of the sectors in each list (using a Kendall correlation) showed a significant relationship ($T = .38$, $p = .000$), indicating a partial matching of sector complexity ratings based on the two different approaches.

2.5.5 Complexity Similarity Ratings.

There was 1 set of proximity measures for each of the 5 FPLs from each of the 5 specialization areas, for a total of 25 matrices, and 1 set from each of the 5 Developmentals. There were also six sets of proximity measures for most of the sectors from the APSs and TMU staff.

MDS was applied to the controller and APS/TMU similarity judgments to explore the structure of the complexity judgment data. The FPL and Developmental data will be discussed separately from the APS and TMU results, given that much smaller sets of proximity measures (i.e., similarity judgments) were collected from the former groups.

TABLE 6. WEIGHTED RATINGS OF JACKSONVILLE ARTCC SECTORS. EACH RATING IS THE SUM OF THE PRODUCTS OF AVERAGE RATING OF EACH SECTOR AND THE AVERAGE RATED IMPORTANCE OF THE FACTOR.
ALSO SHOWN ARE THE FAA COMPLEXITY RATINGS FROM THE 1991 ANNUAL REVIEW OF JACKSONVILLE ARTCC SECTORS.

SECTOR	WEIGHTED RATING	FAA RATING
OCALA	45301.72	196
CEDAR KEY	41341.93	188
CRESTVIEW	31270.32	218
AIKEN	27029.61	96
ALLENDALE	23932.79	258
LAKE CITY	23713.79	205
ST. JOHNS	22394.25	131
PERRY	21374.25	196
BRUNSWICK	20438.09	212
FLORENCE	20236.97	186
ST. AUGUSTINE	20178.89	134
SEMINOLE	18600.42	139
WAYCROSS	18508.47	188
COLUMBIA	14849.21	160
MAYO	12766.11	161
SUMMER	12430.99	115
GAINESVILLE	12053.46	100
STATES	11039.12	120
GREEN COVE	10589.46	115
TAYLOR	10573.83	125
ALBANY	10498.25	128
JEKYL	9297.21	182
ASHBURN	9141.05	154
ALMA	8426.24	112
SILVER SPRINGS	7835.13	235
CHARLESTON	7081.30	121
MYRTLE	6661.58	137
BREWTON	4607.63	104
GENEVA	3671.23	104
TALLAHASSEE	3367.96	169
KEYSTONE	2979.80	137
HUNTER	2904.09	161
MOULTRIE	2571.88	133
GEORGETOWN	2293.17	104
METTA	1788.94	109
RIDGEWAY	1716.94	95
TORRY	1235.84	124
NEPTA	1117.59	113

2.5.6 MDS.

2.5.6.1 FPL and Developmental Data.

INDSCAL was used to analyze the complexity similarity data. INDSCAL produces a common stimulus space shared by the participants, and indicates individual differences in their use of the identified dimensions. In the case of the FPLs and Developmentals, solutions were restricted to two dimensions, because of the limited number of stimuli.[6] Interpretation of the MDS stimulus spaces for each of the specialization areas was accomplished by using sector descriptions and ratings of each sector on the previously discussed initial set of 24 complexity factors. Copies of the stimulus spaces were also sent to Jacksonville ARTCC personnel for their review and interpretation.

Dimensions were named by determining whether the arrangement of sectors along each MDS dimension corresponded to the increase or decrease in some variable or factor related to complexity. In some cases, interpretation was difficult; nevertheless, it was possible to label most of the dimensions. Details of these analyses are found in appendix B.

2.5.6.2 Summary of Dimensions.

Listed below are the dimensions identified by means of MDS for each of the specialization areas. Each dimension is assumed to represent a potential complexity factor. (See table 7 for a list of the factors, with redundancies removed.)

Table 7. MDS Factors from FPLs in Five Specialization Areas and Frequency of Occurrence of Each Factor

FACTOR	FREQ.
TYPE OF TRAFFIC (OVERFLIGHTS VS. CLIMB/DESCEND)	3
VOLUME	2
VFR VS. IFR	2
NUMBER OF TRAFFIC DIRECTIONS (CROSSING VS. ONE-WAY)	1
NUMBER OF PROCEDURES	1
MULTIPLE FUNCTIONS	1
MILITARY TRAFFIC	1
FREQUENCY CONGESTION	1
EFFECTS OF TRAFFIC LOAD (MANAGEABLE VS. HECTIC)	1
AMOUNT OF COORDINATION	1
ALTITUDE (LOW, MORE COMPLEXITY)	1

6 The similarity judgment data were assumed to be at the ordinal level of measurement; therefore, a non-metric MDS model was employed. Although it could be argued that the data were measured at the interval level, the more conservative approach of assuming the ordinal level was chosen. The use of metric versus non-metric MDS did not, in fact, make a great difference in the resulting stimulus space configurations.

NORTH

1. Frequency congestion
2. Effects of traffic load (manageable vs. hectic)

SOUTH

1. Visual Flight Rules (VFR) vs. Information Flight Rules (IFR), non-professional vs. professional pilots
2. Volume, type of traffic (overflights vs. arrivals/departures)

EAST

1. Number of traffic directions (crossing vs. one-way)

WEST

1. Volume, military traffic
2. Type of traffic (overflights vs. arrivals), VFR vs. IFR, number of procedures, altitude (high vs. low)

CENTRAL

1. Amount of coordination, multiple functions
2. Type of traffic (overflights vs. climb/descend)

DEVELOPMENTALS

1. West vs. East, crossing traffic vs. one-way traffic
2. Large vs. small airspace, low vs. high problems with sector boundaries

2.5.6.3 Airspace Procedures and TMU Personnel.

The data sets for Airspace Procedures and TMU participants were combined for analysis using INDSCAL. Since different participants made comparisons between different sets of sectors, depending upon their familiarity with the airspace, a common set had to be derived for the Airspace Procedures and TMU INDSCAL analyses. The TMU participants had 19 sectors in common, but the APSs had only 9 sectors in common. These common sector sets were used in the INDSCAL analysis. The details of these MDS analyses are found in appendix B. The resulting sets of complexity factors are shown in tables B1 and B2.

2.5.7 WSST.

The WSST is a measure of cognitive style (Galin and Ornstein, 1974). It assesses whether an individual tends to solve problems using verbal or analytical thinking, as opposed to spatial or global thinking. The total possible score is 60. A high score indicates a preference for verbal/analytical processing, while a low score suggests a preference for spatial/global processing. A score of 30 means that there is no strong tendency. The test was used in an attempt to explain individual differences in similarity judgments.

A number of analyses showed that there were no differences in cognitive style between the various controller groups, and that WSST scores did not appear to explain any differences in MDS results between controllers. (See appendix C for details.)

2.6 DISCUSSION.

The preliminary and main studies produced three kinds of data about sector complexity, from three sources. The first kind of data was the rankings of sectors for complexity, which were available from the sector sorts. These rankings helped determine the most complex sectors in the Center, and they can be compared to the overall ratings of sectors on the 24 Initial Factors. The second kind of data were the factor names listed by the preliminary and main study participants. The frequency with which factors were mentioned on these lists can be compared between the preliminary and main studies, and contrasted to the ratings of factor importance collected during the main study.

The third kind of data also identified factors, but came from a different source: the complexity similarity judgments. Although sorts and lists were relatively direct methods of gathering information on sector complexity, similarity judgments were the outcome of a more indirect approach. Use of this method assumed that valuable insights about complexity factors might be obtained by asking participants to make comparisons that drew upon their knowledge of the Jacksonville sectors. What they may not have been able to report verbally, they may have been able to demonstrate in their judgments. The judgments themselves were submitted to MDS analysis, and factor names were developed on the basis of the dimensions that emerged from the MDS results. Accordingly, the MDS results will be discussed, in addition to the data obtained from the sorts and lists.

2.6.1 Sector Complexity and Difficulty.

One hypothesis of this study was that sector complexity and sector difficulty would be highly related, with difficulty being the air traffic controller's subjective response to complexity. This was confirmed by the high correlation of APS ratings of sector complexity and difficulty in the preliminary study. Therefore, the sector complexity factors derived from this study should assist in determining which sectors in the Jacksonville ARTCC are most complex and most difficult to work.

2.6.2 Sector Sorts.

The preliminary study was a convincing demonstration, on a limited basis, of substantial agreement between controllers about the complexity of sectors, as demonstrated in a sorting exercise. Correlations of sector sorts between individual controllers from the West Specialization Area were significant, and the degree of overall agreement between them was also significant.

This was also the case in the main study where FPLs and Developmentals sorted sectors within their specialization areas. Degree of agreement among rankings was significant within each area. The sector judged most complex by the four West Area FPLs in the preliminary study (Crestview) also attained the highest average rank in the main study, where similar sorts were completed by five different West Area controllers.

Upon comparing the ordering of sectors from FPL sorts in each area to the sectors obtaining the highest weighted sum of factor ratings in the main study (table 6), it was found that two of the sectors at the top of the sector sorts, Crestview (West) and Aiken (East), were also on the list of the five highest-rated sectors. The highest-rated sectors from the other three specialization areas were found in lower ordinal (sorted) positions. In the South Area, St. Johns and St. Augustine (tied for first by sorting) were ranked seventh and eleventh (respectively) on the rating list; Brunswick (North) was ninth; and Seminole (Central) was twelfth.

A more comprehensive check, on the correspondence of the area sorts and the ratings of sectors on factors, was conducted by noting, for the sectors in each specialization area, the order of their appearance in table 6 (weighted sector ratings). The purpose of this check was to evaluate the comparability of the two methods: sorting and rating. Kendall correlations were then calculated, comparing the sort order with the rating order for each area. The results are shown in table 8.

Table 8. Correlation of Sector Rankings with Ratings of Sectors on Preliminary Complexity Factors

SPEC. AREA	KENDALL'S TAU	SIGN.
NORTH	.71	.005
SOUTH	.95	.002
EAST	.62	.007
WEST	.98	.001
CENTRAL	.39	.390

All but one of the correlations in table 8 were significant. The correlation coefficients for the South and West Specialization Areas, in particular, indicated a high level of agreement. In the case of the West Area, for example, the complexity rankings from sorting would have been identical to those for the complexity-based ratings, except that two sectors in the sorted list were tied. These results suggest that the two methods of determining sector complexity usually yield comparable results.

2.6.3 Complexity Factors.

The first attempt (in the preliminary study) to gather complexity factors, by simply asking APSs and FPLs to list them, produced 61 factors. Because some of these were repeated more or less verbatim by several participants (see table 1), it was possible to reduce the list to 19 factors. The first 7 factors accounted for 64 percent of the 61 factors mentioned. The first factor (Restricted Areas, Warning Areas, MOAs, and Notification Time) was mentioned by 8 of the 10 respondents (for 13 percent of the total).

A second list of 215 complexity factors was gathered during the main study. Removal of redundancies resulted in a list of 19 factors as found in table 4. A comparison of tables 1 and 4 shows that the following factors are near the top on both lists: Complex Flight Paths; Restricted Areas, Warning Areas, and MOAs; Weather; Size of Airspace; and Traffic Volume. However, a comparison of tables 4 and 5 (ratings of factor importance) does not show much agreement, except about Restricted Areas, Warning Areas, and MOAs; Weather; and Coordination.

It might be assumed that the frequency of a factor's being mentioned was related to its importance to the group of FPLs. Given the above results, this assumption seems uncertain, and it was investigated further in section 2.8.

2.6.4 Complexity Similarity Judgements.

In the preliminary study, the four FPLs were asked to compare pairs of West Area sectors for similarity in complexity. Overall tests of the agreement of the four participants indicated a significant level of accord.

The high correlations of similarity between individual participants' judgments for photographs and maps, indicated that the photographs and maps of sectors were, for all practical purposes, interchangeable as the basis for collecting complexity similarity judgments. Although controllers from different areas of the Center tended to prefer the representation they worked with most often, photos and maps both seemed to provide adequate stimuli for the recall, not only of the physical attributes of the airspace, but also of the typical traffic patterns, weather activity, and so forth. Participants discussed these various aspects of sectors when presented with photographs or maps of the airspace (without traffic).

The INDSCAL MDS spaces for the West Area photographs and maps were very similar. In spite of the differences between individual sets of similarity ratings, the MDS INDSCAL software was able to derive a shared stimulus space that accounted for 91 percent of the variability in the set of judgments. Thus, the degree of concordance between the four FPLs, which emerged when the judgments themselves were compared, was reflected in a well-fitting shared stimulus space.

In the main study, as in the preliminary study, there was generally a high degree of agreement about which sectors within each specialization area were similar in complexity. The only exception was the East Area, where the level of controller agreement was marginal.

Combining the sector complexity similarity judgments, within each specialization area using INDSCAL, was successful in that the common stimulus space for each group efficiently accounted for controller data in each case.

Upon considering individuals within each area, it was found that the amount of variance in judgments, accounted for by INDSCAL, was generally above 0.60. However, some participants in each area were not well represented by the common MDS space, indicating that there was not always agreement within each group regarding the complexity factors used to make the similarity judgments. For those participants who were adequately represented, there were differences in each controller's emphasis on the identified common dimensions.

The intention of collecting data on thinking style (in this case, the WSST) was to assist in explaining individual differences in participants' cognitive structures and decision-making patterns. At this stage of the study, the primary information on variations in cognitive structures emerged from the INDSCAL weight spaces. These data illustrated how heavily each participant used the common dimensions identified for the group of five controllers within each specialization area. However, it appears that cognitive style (as measured by the WSST) did not account for individual differences in knowledge structures in this case.

It was possible to compare the MDS results, for the preliminary and main studies, only for the West Area. The description of the two dimensions in each solution was almost identical. The close correspondence of the MDS dimensions from two different groups of West Area FPLs suggests that the procedure is a reliable means for identifying complexity factors.

The list of dimensions, collected from the interpretations of the FPL MDS spaces in the main study, contained only three factors that were repeated more than once. Type of Traffic (overflights vs. climbing/descending), Traffic Volume, and VFR vs. IFR traffic appeared three, two, and two times, respectively. The remaining eight factors appeared only once in the list (table 7). Due to the differences in the characteristics of sectors in each specialization area, it is understandable that there might have been variations in complexity factors.

It is interesting to note that there was some correspondence in the East FPL and Developmental MDS results. (The Developmentals were being trained in the East Area.) This suggests that it might be possible to use MDS as a method for assessing progress in training. Training success might be indicated when Developmentals' cognitive structures (as measured by MDS) begin to resemble those of their instructors. This method of assessing training effectiveness could be used to complement other methods. It is attractive in that it does not depend on supervisor ratings.

The INDSCAL stimulus spaces for the Airspace Procedures and TMU participants accounted for a large proportion of the information in the original similarity judgments, and each participant was well represented. Participants differed to some extent in their use of the available dimensions in making their judgments. The statistical approach employed for interpretation resulted in many factors being identified, especially in the three-dimensional TMU stimulus space. Each of the property vectors[7] was effective in locating meaningful complexity factors, and did an excellent job of explaining the pattern of sectors in the MDS stimulus space.

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7 See appendix B for an explanation of property vectors.

Upon comparing the property vectors for the Airspace Procedures and TMU INDSCAL stimulus spaces (tables B1 and B2), it was discovered that all but one of the vectors identified for the APS INDSCAL solution were found in the TMU results. The missing factor, Coordination, is closely related to Number of Facilities, and was one of the factors present in the TMU vectors. Thus, there was strong agreement between the APS and TMU participants regarding complexity factors.

Of the 11 factors that emerged from the INDSCAL results for the 5 specialization areas (table 7), 6 matched those found in the total of 18 APS or TMU property vectors (tables B1 and B2), as shown :

Table 9. Relationship Between Specialization Area Factors and APS/TMU Factors.

SPEC. AREA FACTOR	APS/TMU FACTOR
Type of traffic	Climbing/Descending Flights
VFR vs. IFR	Aircraft Mix
No. of Traffic Directions	Intersecting Flight Paths
No. of Procedures and Multiple Functions	Multiple Functions
Military Traffic	Frequent Military Requirements
Coordination	Coordination

The most noticeable omissions (factors present in the FPL MDS results but absent from the APS/TMU lists) were Frequency Congestion, Volume, and Altitude. Number of Procedures was also missing, but is probably closely related to Multiple Functions. Considering that different approaches were used to derive the sets of MDS dimensions, a respectable degree of agreement nevertheless emerged.

2.6.5 Comparison of Direct and Indirect Methods.

A comparison of the MDS results (tables 7, B1, and B2), with the compilation of factor lists found in table 4, shows that eight of the first nine factors of table 4 are also found in the MDS results. These factors accounted for 48 percent of those mentioned. Table 10 lists the factors from table 4, and their correspondence with the MDS results.

In some cases, factors that occurred frequently, or were particularly salient property vectors in the FPL, APS, and TMU MDS results, appeared low in frequency of occurrence on the summary of factor lists (table 4). Examples are VFR vs. IFR Traffic, Number of Departing/Arriving Aircraft, Multiple Functions, and Climbing/Descending Flights.

A factor that appeared in three cases in the FPL MDS dimensions was not included in the factor lists from table 4; this was, Type of Traffic (Overflights vs. Arrivals). However, this could be related to Number of Climbing vs. Descending Flights. Factors from the Airspace Procedures/TMU MDS results, which did not appear in table 4, included Airline Hubbing, Number of Facilities, and presence of Standard Terminal Arrival Routes (STARS) and Standard Instrument Departures (SIDS). On the other hand, several factors mentioned fairly often in table 4 did not emerge in the MDS results. These included Sector Boundaries, Flow Restrictions, and Transitioning Traffic. Although there was some agreement between the direct and indirect approaches, some factors emerged from each source that were not common to both.

Table 10. Comparison of Factors from Lists and Factors from FPL, APS, and TMU MDS Results

FACTORS FROM LISTS	MDS CORRESPONDENCE
COMPLEX FLIGHT PATHS	FPL, TMU
RESTRICTED AREAS, WARNINGS, MOAS	
SIZE AIRSPACE	TMU
TRAFFIC VOLUME	FPL
WEATHER	TMU
ARRIVAL/DEPARTURE SEQUENCING/SPACING	APS, TMU
COORDINATION	FPL, APS
MILITARY TRAFFIC	FPL, TMU
AIRCRAFT MIX	APS, TMU
SECTOR BOUNDARIES	
FLOW RESTRICTIONS	
TRANSITIONING	
CLIMBING/DESCENDING FLIGHTS	APS, TMU
DEPARTING/ARRIVING AIRCRAFT	APS, TMU
EQUIPMENT	TMU
FREQUENCY CONGESTION	FPL
IRREGULAR ALTITUDE STRATIFICATION	
VFR VS. IFR	FPL, APS, TMU
MULTIPLE FUNCTIONS	FPL, APS, TMU

Based on these sources, it was possible to generate a list of complexity factors for further analysis. First, the following factors, shared by at least two of the three MDS lists (tables 7, B1 and B2) were considered important and were included:

a. Type of Traffic (overflights vs. climbing/descending)
b. Aircraft Mix (VFR vs. IFR)
c. Intersecting Flight Paths
d. Multiple Functions
e. Military Traffic
f. Coordination

In addition, one item in table 7 emerged more than once, but was not in the common list: traffic volume.

The following items in tables B1 and B2 appeared meaningful, but were not in the above lists:

a. Number of Facilities.
b. Number of Departing/Arriving Aircraft.
c. Airline Hubbing.
d. Weather.

The direct approach resulted in several factors being mentioned frequently in table 4, but not included in the MDS-derived lists:

a. Complex Flight Paths.

b. Restricted Areas, Warning Areas, and MOAs.

c. Size of Airspace.

d. Arrival Departure Sequencing/Spacing.

e. Equipment or Radio/Radar Coverage (also appeared in table B2).

f. Frequency Congestion (also appeared in table 7).

To these were added two other factors assumed to be highly correlated with those listed. This was done to determine whether they were independent factors or, as expected, highly related with those already under consideration. At the recommendation of Jacksonville ARTCC staff, Manageability of the Sector under Increasing Traffic Load (which emerged from the FPL MDS analysis) was included in the list. It was assumed that this factor would be nearly identical to Traffic Volume.

Center staff suggested that Multiple Functions and Number of Procedures (both of which emerged in the FPL MDS results) were probably closely related. To verify this, Number of Procedures was added to the list. This resulted in a set of 19 Candidate Factors (as shown in table 11), which were used in the next part of the research.

2.7 INTERIM PHASE I CONCLUSIONS.

Ratings of sectors on complexity and difficulty indicated a high degree of relationship between the two concepts. A complex sector is also a difficult one. The development of improved metrics for assessing complexity will, therefore, be helpful in identifying sectors that are difficult to manage, and in specifying factors that contribute to high controller workload.

The two kinds of stimuli (maps and photographs) chosen to represent sectors in the preliminary study, yielded comparable judgments and MDS solutions. This finding is useful for future work, in that, sector maps (without traffic) have been found to be an acceptable stimulus for making comparisons, and gaining other information about sectors. Screen photographs could also be used, but are initially more difficult to acquire.

Controllers from the five specialization areas in the Jacksonville ARTCC generally agreed about overall sector complexity as determined by sector sorts. In addition, the order of complexity of sectors, within each area, corresponded well with the ranking of sectors for complexity, based on a set of ratings gathered from the same participants. Sorting, therefore, appears to be a useful method for determining complexity.

Compiling suggested complexity factors, from lists by study participants, generated two lists, one from the preliminary study, and another from a larger number of controllers in the main study. There was some correlation between the lists, and the main study list was used in later comparisons with the MDS results. When factors from the preliminary study list were ordered by ratings of importance, however, there was not much agreement with the frequency of occurrence of factors suggested by the same participants. This finding indicates that, although a factor might have been mentioned frequently, its rate of occurrence may not be an accurate indicator of its importance.

Table 11. List of Candidate Sector Complexity Factors

1.	THE RELATIVE FREQUENCY OF OVERFLYING VERSUS CLIMBING/ DESCENDING TRAFFIC.
2.	THE DEGREE OF AIRCRAFT MIX (VFR, IFR, PROPS, TURBOPROPS, JETS, ETC.).
3.	THE OCCURRENCE OF INTERSECTING AIRCRAFT FLIGHT PATHS.
4.	THE EXTENT TO WHICH THE CONTROLLER MUST PERFORM MULTIPLE FUNCTIONS (APPROACH CONTROL, TERMINAL FEEDER, EN ROUTE, IN TRAIL SPACING, ETC.)
5.	THE AVERAGE AMOUNT OF MILITARY TRAFFIC.
6.	THE NEED FOR COORDINATION (WITH OTHER SECTORS, CENTERS, APPROACH CONTROLS, MILITARY FACILITIES, ETC.).
7.	THE AVERAGE VOLUME OF TRAFFIC.
8.	HOW MANAGEABLE A SECTOR IS AS TRAFFIC VOLUME INCREASES.
9.	THE NUMBER OF DIFFERENT PROCEDURES A CONTROLLER MUST BE FAMILIAR WITH AND EMPLOY IN ORDER TO OPERATE THE SECTOR.
10.	THE NUMBER OF FACILITIES ACTUALLY DEALT WITH UNDER NORMAL CONDITIONS (OTHER SECTORS, CENTERS, APPROACH CONTROLS, MILITARY FACILITIES, ETC.).
11.	THE AVERAGE NUMBER OF DEPARTING AND ARRIVING AIRCRAFT.
12.	THE EXTENT TO WHICH THE CONTROLLER'S WORK IS AFFECTED BY AIRLINE HUBBING.
13.	THE DEGREE TO WHICH WEATHER PROBLEMS AFFECT AIR TRAFFIC CONTROL OPERATIONS.
14.	THE RELATIVE FREQUENCY OF COMPLEX AIRCRAFT ROUTINGS AS OPPOSED TO DIRECT ROUTINGS.
15.	THE EXTENT TO WHICH THE CONTROLLER'S WORK IS AFFECTED BY RESTRICTED AREAS, WARNING AREAS, AND MOAs.
16.	THE SIZE OF SECTOR AIRSPACE.
17.	THE NEED FOR ARRIVAL/DEPARTURE SEQUENCING AND SPACING.
18.	THE ADEQUACY OF RADIO AND RADAR COVERAGE.
19.	THE AMOUNT OF RADIO FREQUENCY CONGESTION DURING PEAK TRAFFIC PERIODS.

It was possible to determine the most complex sector in each specialization area from the sector sorts. An overall ranking of sector complexity for all 38 Jacksonville sectors was accomplished by adding up ratings on 24 Initial Factors, multiplied by the importance rating of each factor. There was a relatively low but significant correlation between the order of the list based on factor ratings, and the list from the FAA annual review. However, this correlation was not strong enough to indicate a meaningful relationship between the two complexity measures. Confirmation of this will require further study.

In both the preliminary and main studies, similarity judgments of sector complexity indicated some individual differences, but there was sufficient agreement that common MDS stimulus spaces could be derived for each specialization area, the Developmentals, and the Airspace Procedures/TMU staff. Individual differences emerged, however, in the weight spaces for each solution, where participants varied in the amount of emphasis they placed on a given dimension. A test of thinking style, the WSST, did not account for the differences in perception of sector complexity.

Different approaches (subjective and statistical) were used to interpret the MDS spaces in the main study. When comparing the resulting factors, there was considerable agreement between the APS and TMU results, both of which used the statistical approach. There was also some similarity between the FPL factors and the APS/TMU data (subjective versus statistical approach), although some mismatches were evident.

Emerging from this work is a list of potential complexity factors, some of which were common to both direct and indirect approaches, and some of which were unique. There is, as yet, no information to indicate which factors are most important in accounting for sector complexity. It is evident that some of the factors are related. In the next phase of the study, further work was completed to determine which Candidate Factors were correlated, and how adequately they account for sector complexity.

2.8 FACTOR SELECTION.

The goals of this part of the Phase I research were to reduce the 19 Candidate Factors to a more compact set, and to verify that the reduced set of factors could adequately account for overall sector complexity.

2.8.1 Method.

2.8.1.1 Participants.

Volunteer participants included 25 FPLs, 5 TMU controllers, and a controller from Military Operations. FPL participants were drawn, based on availability, from those working on the control room floor on the days of the researchers' visits to the Center. Five of the FPL participants had also participated in the factor development phase of the study. The other participants were selected on the basis of their availability; three of these individuals had also participated in factor development.

2.8.1.2 Materials.

Data collection materials for the FPLs included 3 kinds of paper forms designed to collect ratings of the sectors in each specialization area on the 19 Candidate Factors listed in table 11. Ratings were needed to assess the importance of the factors, and to rank the sectors on complexity. Information was also collected on participant age and years of experience. TMU and supervisory controllers used a different form, which was designed to record ratings of overall complexity on all 38 sectors in the Jacksonville ARTCC.

2.8.1.3 Procedure.

The FPL forms were combined into a package, and administered to participants who were available from the control floor. Five FPLs from each specialization area first sorted maps of the sectors comprising their area into order of overall complexity. They then rated the sectors in their areas on all of the 19 Candidate Factors. Finally, they evaluated the importance of each factor on a seven-point scale. TMU participants completed their ratings in their offices. They rated all the sectors in the center on overall complexity. In each case, the researchers provided instructions and answered questions, as needed.

2.9 RESULTS AND DISCUSSION.

2.9.1 Agreement Between Participants.

In order to check on the agreement between the 5 FPLs in each specialization area, product-moment correlations of the sector complexity ratings using the 19 Candidate Factors were calculated. In every area, except one, correlations between participants were significant. In the Central Specialization Area, however, one participant's ratings were significantly correlated with two of the others, but not with the other two controllers. After analysis of the data, it was decided to retain this participant's ratings for further analysis. (Removing this participant from the analysis did not, in fact, substantially alter the results reported below.)

The six TMU and supervisory controllers (who were familiar with the Center's airspace in general), rated all 38 sectors in overall complexity. The product-moment correlations between their ratings were significant, except for one case. One rater's results did not correlate with any of the others. Further investigation revealed that five of the six controllers who rated the overall complexity of the sectors were, or had recently been, employed in the TMU, where they performed flow-control functions. One controller, however, was working in Military Operations and had not controlled air traffic for several years. It was this participant's ratings which did not correlate with the other controllers' evaluations of overall sector complexity. Therefore, this rater's results were excluded from the set, and the judgments of the five remaining TMU personnel were averaged to create a measure of overall sector complexity. This measure was called the "Complexity Criterion."

2.9.2 Importance of Factors.

The next step was to identify the most important subset of the 19 Candidate Factors for determining airspace complexity. First, an overall sector complexity score was calculated by averaging the ratings each sector received from 5 FPLs on each of the 19 Candidate Factors. All 19 scores were then added together for each sector, resulting in a "Sector Complexity Index." By combining the results for sectors from all specialization areas, a set of Complexity Indices for all 38 sectors in the Center was developed.

When the set of complexity indices derived from all 19 factors was correlated with the Complexity Criterion provided by the 5 TMU controllers, a significant product-moment correlation was obtained ($r = .63$, $p < .01$). This finding indicated that a simple, non-weighted sum of all of the Candidate Factors was moderately successful in accounting for the information in the Complexity Criterion. It was reasonable to assume, however, that a subset of these factors would do an equal or better job of accounting for overall complexity.

As a basis for identifying such a subset of factors, separate correlations were calculated between the set of sector scores on each of the 19 Candidate Factors, and the set of Complexity Criterion scores. (That is, between scores for all 38 sectors on factor 1 and Complexity Criterion scores for the same sectors, then for factor 2 and criterion scores, etc.) The results provided an ordering of the complexity factors by the size of their product-moment correlations with the criterion (table 12). It was evident that the first factor alone, Routings (the proportion of complex, as opposed to direct, aircraft routings), had a higher correlation, with overall complexity, than complexity indices based on the sum of all 19 factors. Those 11 Candidate Factors, with significant simple correlations with overall sector complexity, were called Final Factors.

Table 12. Product-Moment Correlations of Sector Complexity Scores with the Complexity Criterion on 38 Jacksonville Sectors. (The "NO." column refers to the full description of the variables in Table 7. "NS" denotes the lack of a significant correlation.)

NO.	VARIABLE	PEARSON r	SIGNIFICANCE
14	ROUTINGS	.73	$p < .01$
17	SPACING	.68	$p < .01$
19	CONGEST	.62	$p < .01$
4	FUNCTION	.56	$p < .01$
3	INTERSECT	.53	$p < .01$
7	VOLUME	.52	$p < .01$
9	PROCEDURE	.42	$p < .01$
12	HUBBING	.40	$p < .05$
6	COORDINATE	.37	$p < .05$
13	WEATHER	.37	$p < .05$
8	MANAGVOL	.34	$p < .05$
1	OVERFLY	.32	NS
11	DEPARR	.29	NS
18	COVERAGE	.24	NS
5	MILITARY	.15	NS
15	RESTRICT	.10	NS
10	FACILITY	.04	NS
2	MIXTURES	-.03	NS
16	SECSIZE	-.14	NS

Multiple regression[8] was then used to determine which Final Factors were most salient in accounting for overall sector complexity (see table 13). Although table 12 shows that seven of these factors had significant individual correlations with the Complexity Criterion, they were also correlated with each other (or were redundant to some degree). Table 14 shows a correlation matrix of all the Final Factors. The regression analysis took these correlations into account and estimated only the unique contribution (or lack thereof) of each variable in accounting for overall sector complexity. The resulting multiple correlation (R = .85) was quite high, indicating that the identified variables were successful in predicting overall sector complexity.

FPLs from each specialization area had also rated the importance of the 19 complexity factors. There was a significant level of overall agreement between the controllers on the importance of the Candidate Factors as evaluated by a Kendall correlation $\chi^2(25, N = 5) = 98.19$, $p = .0000$. It was found that the importance ratings were not effective in identifying any factors related to overall complexity.

Given the above results, it appears that overall sector complexity, as defined by the ratings of a group of TMU controllers, can be predicted by as few as three of the Candidate Factors. These are Routings (the proportion of complex, as opposed to direct, aircraft routings); Spacing (need for arrival/departure sequencing and spacing); and Congestion (radio frequency congestion). This finding suggests that estimates of sector complexity could be made on a very straightforward basis, using only a limited number of factors.

2.9.3 Factor Intercorrelations.

It should not be assumed, however, that these factors are the only ones involved in complexity. As table 12 demonstrates, several other Final Factors were also strongly related to overall complexity. For example, the regression formula using the next three most highly correlated factors (Number of Multiple Functions, Traffic Volume, and Number of Intersecting Airways) with overall complexity was also effective in predicting complexity. Routings, Spacing, and Congestion were highly correlated with other factors and can be considered representative of them in the regression equation reported in table 13. These intercorrelations indicate that many of the complexity factors tended to occur together in complex sectors in the Jacksonville ARTCC.

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8 Multiple regression is a statistical technique that draws a relationship between a set of measures or variables and some other variable of interest. A formula is created that shows the proportion of each of the "predictor" variables that must be added together to best predict or account for the "outcome" variable.

Table 13. Multiple Regression Results using the Complexity Criterion as the Dependent Measure and Complexity Factors as Independent Variables

Multiple R	.85
R Square	.72
Adjusted R Square	.69
Standard Error	.55

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	3	26.45	8.82
Residual	34	10.38	.31

F = 28.88 Signif F = .0000

------------------ Variables in the Equation ----------------

Variable	B	SE B	Beta	T	Sig. T
ROUTINGS	.44	.13	.39	3.35	.0020
SPACING	.23	.07	.37	3.47	.0015
CONGEST	.32	.12	.29	2.77	.0087
(Constant)	-.17	.56	-.31	.76	

Table 14. Product-Moment Correlations Between Final Factors. (* - Significant at p <.05, ** - Significant at p < .01)

	CONGEST	CRDINATE	FUNCTION	HUBBING	INTERSCT	MANAGVOL
CONGEST	1.0000	.5004**	.3052	.1734	.4916**	.4573**
CRDINATE	.5004**	1.0000	.6001**	-.0355	.5196**	.6791**
FUNCTION	.3052	.6001**	1.0000	.1102	.4325**	.7186**
HUBBING	.1734	-.0355	.1102	1.0000	-.0394	-.0594
INTERSCT	.4916**	.5196**	.4325**	-.0394	1.0000	.5522**
MANAGVOL	.4573**	.6791**	.7186**	-.0594	.5522**	1.0000
PRCEDURE	.4663**	.6825**	.7557**	-.1567	.5014**	.7140**
ROUTINGS	.4868**	.4877**	.5764**	.1922	.4803**	.3833*
SPACING	.3636*	.2176	.6003**	.6668**	.3164	.2848
VOLUME	.6353**	.1210	.2361	.5512**	.1934	.2719
WEATHER	.3775*	.1166	.2285	.3121	-.0174	.0024

	PRCEDURE	ROUTINGS	SPACING	VOLUME	WEATHER
CONGEST	.4663**	.4868**	.3636*	.6353**	.3775*
CRDINATE	.6825**	.4877**	.2176	.1210	.1166
FUNCTION	.7557**	.5764**	.6003**	.2361	.2285
HUBBING	-.1567	.1922	.6668**	.5512**	.3121
INTERSCT	.5014**	.4803**	.3164	.1934	-.0174
MANAGVOL	.7140**	.3833*	.2848	.2719	.0024
PRCEDURE	1.0000	.4632**	.3312*	.2114	.1920
ROUTINGS	.4632**	1.0000	.5261**	.3088	.2677
SPACING	.3312*	.5261**	1.0000	.5043**	.3811*
VOLUME	.2114	.3088	.5043**	1.0000	.4937**
WEATHER	.1920	.2677	.3811*	.4937**	1.0000

Table 15. Most Important Complexity Factors, the Basis for their Measurement, and their Appearance on Lists of Candidate Factors using Direct and Indirect Approaches in Phase I. (An N/A is shown where it was not possible for the variable to emerge in the MDS analysis given the interpretation method involved.)

SECTOR	MEASUREMENT	FPL LIST	FPL MDS	APS MDS	TMU MDS
ROUTINGS	SPECIALIST OPINION	X		N/A	N/A
SPACING	BASED ON SECTOR DATA	X			
CONGEST	BASED ON ANALYSIS OF VOICE TAPES	X	X		
FUNCTION	BASED ON SECTOR DATA	X	X	X	X
INTERSECT	BASED ON SECTOR DATA		X		X
VOLUME	BASED ON SECTOR DATA	X	X		
PROCEDURE	SPECIALIST OPINION		X		
HUBBING	BASED ON SECTOR DATA				X
COORDINATE	SPECIALIST OPINION	X	X	X	
WEATHER	BASED ON SECTOR AND WEATHER DATA	X			X
MANAGVOL	SPECIALIST OPINION		X	N/A	N/A

During the factor identification process, two factors included as candidates for further study were assumed to be highly correlated with other factors in the list. These were Manageable Volume (thought to be correlated with Volume) and Number of Procedures (thought to be correlated with Multiple Functions). When product-moment correlations were calculated between all of the Candidate Factors, it was found that, contrary to predictions, the correlation between Manageable Volume and Volume was not significant. Apparently the number of aircraft typically found in a sector is not necessarily related to how difficult the sector is to control as traffic increases. Observations indicated that the interaction of traffic volume and other sector characteristics, such as sector size, determined difficulty. As predicted, there was a high correlation between Number of Procedures and Multiple Functions. It appears that these two measures are strongly related.

Other significantly related measures from the correlation matrix included Type of Traffic (overflights vs. climbing/descending) and Number of Departing/Arriving Aircraft; Type of Traffic and Multiple Functions; Manageable Volume and Multiple Functions; Number of Procedures and Manageable Volume; and Aircraft Mix and Military Traffic. Sector Size and Type of Traffic were strongly negatively correlated. (Values of "r" and obtained probability levels can be inspected in table 14.)

The correlations between the 19 Candidate Factors listed in table 14 were used as input to Pathfinder. As previously discussed, a Pathfinder network consists of a set of concepts and links that directly connect pairs of highly-related concepts. It was assumed that using correlational data with Pathfinder would assist in the understanding of the relationships between the complexity factors, and would throw light on controller knowledge structures.

Figure 5 shows the Pathfinder network derived from the inter-factor correlations found in table 14. Since correlations, as opposed to proximities (or similarities) were used to generate the network, the links in the graph represent degree of correlation or co-occurrence of the factors in Jacksonville ARTCC sectors.

Inspection of figure 5 indicates three main clusters of factors. Starting at the top, the number of MOAs and Restricted Areas is related to the number of Military Operations. Military Operations, Facilities, and the number of Departing and Arriving Aircraft are related to the Degree of Aircraft Mix. The number of Climbing/Descending (as opposed to overflying) Flights are linked to the presence of Departing and Arriving Aircraft. These factors are also connected with the need for the controller to perform Multiple Functions.

Toward the center of figure 5 is a tight grouping of six factors, including: Multiple Functions, Complex Routings, Number of Procedures, Need for Interfacility Coordination, Manageable Volume, and Number of Intersecting Airways. This clustering indicates that these sector characteristics tend to occur together. Just below this set are two factors involving the Need for Arrival/Departure Sequencing and Spacing and Radio/Radar Coverage. Spacing is related to Airline Hubbing. This last factor appears to be part of another grouping at the bottom of the graph along with Traffic Volume, Frequency Congestion, Sector Size, and Weather.

There is one central node in each of the major clusters. (The factors enclosed in boxes on a Pathfinder graph are called nodes. Nodes are like atoms one sees in a model of a complex molecule. A central node is one that is linked to several other nodes.) The central nodes obtained in this analysis are Aircraft Mix, Multiple Functions, and Traffic Volume. These nodes may represent a primary characteristic of three general types of complex sectors, as defined by the three major clusters identified in this analysis.

When the Final Factors are mapped onto the Pathfinder network, they occupy all but 2 of the 13 factors beneath (but not including) Overfly on figure 5. (Final Factors are shaded in figure 5.) All of the factors in the central group are included in the Final Factors list, indicating that this constellation of complexity characteristics may be critical in defining sector complexity as experienced by en route controllers.

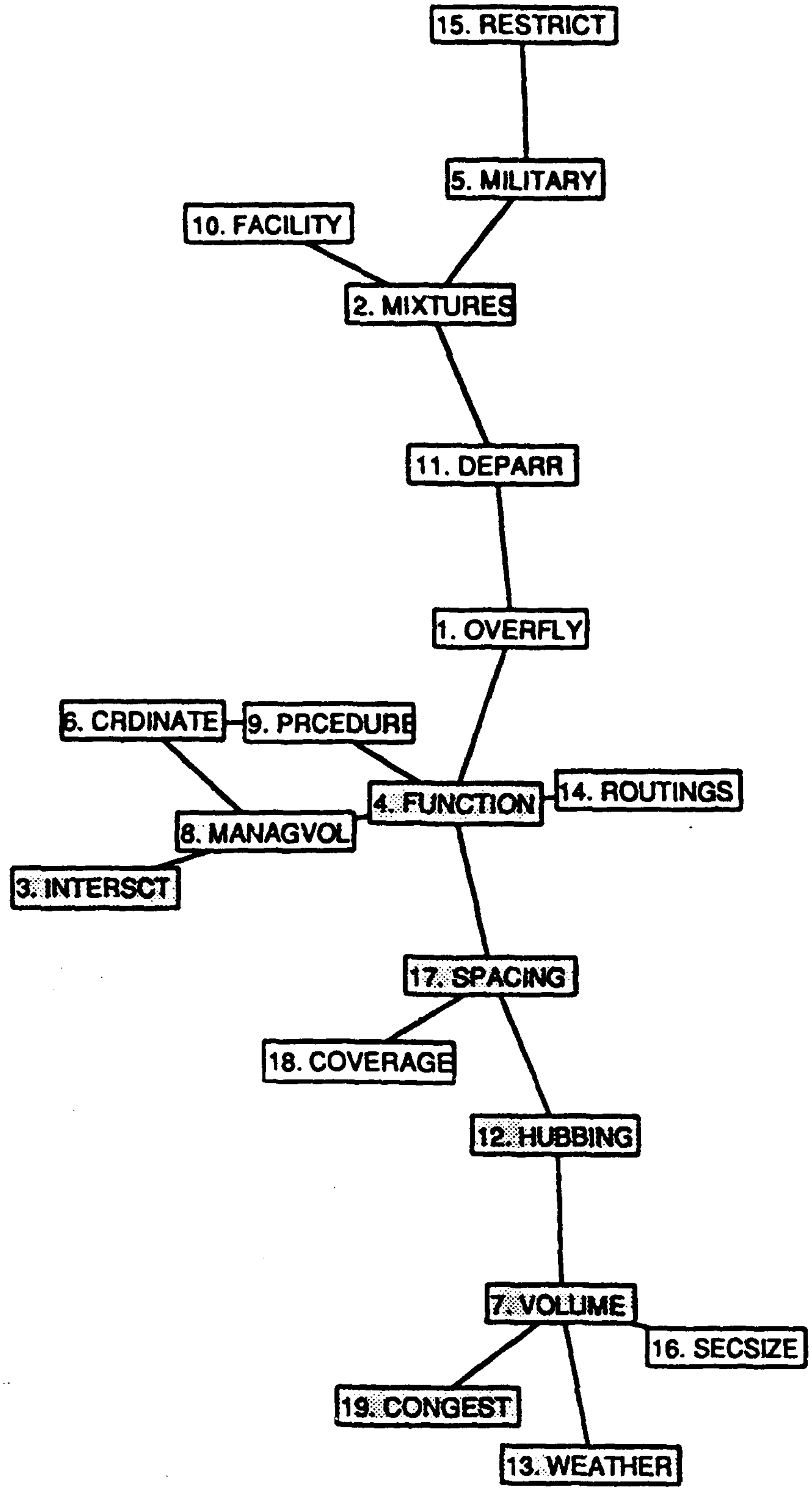

Figure 5. Pathfinder Network Diagram based on the Correlations of 19 Complexity Factors

2.9.4 Evaluating Complexity.

The choice of factors employed to estimate sector complexity should not be based only upon their simple or multiple correlation with the Complexity Criterion, but also on their ease and reliability of measurement. Discussions with the Jacksonville ARTCC staff resulted in the list shown in table 15. This list specifies those factors, taken from the Final Factors, that Center personnel could feasibly measure, even if they were not intimately familiar with all sectors in the airspace.

Although all of the factors are potentially measurable, measurement of some factors would clearly require more effort than others. Those marked as "specialist opinion" need the involvement of FPLs from the specialization area of concern. Evaluation of a sector using the other Final Factors could be handled by generalist personnel (such as airspace planners), with sufficient data, as required.

When the factors requiring specialist opinion were eliminated from the list, and those remaining were entered into a multiple regression procedure, it was still possible to predict overall complexity with reasonable accuracy using only two factors, Arrival/Departure Sequencing and Spacing and Frequency Congestion ($R = .78$, $p < .0000$). This type of approach might make it possible for generalists to assess sector complexity.

2.9.5 Direct Versus Indirect Approaches.

One of the purposes of this research was to evaluate direct versus indirect approaches for exploring controller knowledge about sector complexity. The direct approach involved asking controllers direct questions about sector complexity; the indirect approach was based on statistical analysis of controllers' judgments of sectors similarity in complexity. Armed with the ordering of the complexity factors found in table 12, it was possible to revisit the factor development stage of this study to determine whether one or the other approach showed any advantage. The results of this investigation are also shown in table 15.

One of the Final Factors, Arrival/Departure Sequencing and Spacing, was mentioned in the FPL lists, but was not found in the MDS results. Three Final Factors that emerged from the MDS results were not found in the combined FPL lists: Intersecting Flight Paths, Number of Procedures, and Airline Hubbing. Although these three complexity factors did not appear on the lists given by FPL controllers, they were suggested during the preliminary study by other controllers. These results indicate that, in many cases, direct methods may be adequate for knowledge exploration.

2.9.6 Correlation with FAA Complexity Ratings.

The formula for the regression equation in table 13 was used to calculate complexity indices for all of the Jacksonville sectors. (Ratings for each sector on the factors in the equation were entered in the formula in order to generate an estimate of complexity for each sector.) These indices were then correlated with the Center complexity ratings, based on the FAA formula contained in FAA Order 7210.46. The regression-based complexity indices had low correlations with the FAA scores. There were insufficient operational error data from the Center's records to determine whether or not there was any relationship between the regression-based indices and operational errors.

2.9.7 Refinement of Factors.

Finally, the 19 Candidate Factors under consideration were reviewed by a Jacksonville ARTCC controller who had been extensively involved in the project. This controller and the researchers reviewed the factors and data describing their relative importance and intercorrelations. This team found that it was possible to modify the list by combining redundant factors, and improving the description of each item. The product was a list of 15 factors with definitions and descriptions of their contributions to complexity, as follows:

1. The amount of climbing or descending traffic. Climbing and descending aircraft are those that are transitioning altitudes, including departure and arrival traffic, and aircraft requesting altitude changes due to turbulence, pilot preference, etc.; or aircraft that require different altitudes to alleviate conflictions due to crossing traffic or other problems. Climbing and descending traffic makes maintaining separation more complicated, and increases the number of actions the controller must take and monitor.

2. The degree of aircraft mix (VFR, IFR, props, turboprops, jets, etc.). The performance characteristics of jets versus propeller aircraft, as well as pilot capabilities, can affect the work of the controller. Traffic mix can create problems due to jets overtaking propeller aircraft, limited climb capabilities of propeller aircraft, differences in skill between VFR and IFR pilots, or VFR pilots encountering IFR conditions. Such conditions create additional workload for the controller.

3. The number of intersecting flight paths. This factor represents the number of inherent converging flight paths due to airways, arrival routes, or frequent requests for direct routings. Converging flight paths increase the chance of conflictions.

4. The number of multiple functions the controller must perform (such as approach control, terminal feeder, en route, in-trail spacing, etc.). An ATC function is a related set of tasks or services performed by the controller. A sector that requires numerous functions requires the controller to be familiar with, and perform the tasks associated with each function.

5. The number of required procedures that must be performed (example: all Raleigh arrivals must cross TENNI at FL210). A procedure is a group of tasks, or a specific task, required by regulation or direction. A procedure mandates controller actions and must be performed regardless of other required tasks.

6. The number of military flights. Military flights include all types of military aircraft. Military flights produce complexity due to differences in performance characteristics and nature of mission requirements. Military pilots also have a tendency to make special requests.

7. Amount of coordination or interfacing with other entities (such as adjacent sectors, approach controls, center, military units, etc.). Coordination is communication with other controllers or facilities to discuss critical information regarding air traffic. Coordination requires familiarity with contacting methods, applicable directives outlining procedures between the facilities, and methods for performing coordination activities. In addition, coordination must be performed, as required by the demands of the traffic in the sector.

8. The extent to which the controller is affected by airline hubbing or major terminal/airport traffic. Airports differ in the density of traffic flow in and out of a geographical area. Hubbing refers to the practice of airlines using a central airport for their regional operations. Hubbing and heavy airport/terminal traffic creates a focused concentration of flights in one area with the attendant increase in risk of separation conflicts and number of controller tasks.

9. The extent to which weather-related factors affect ATC operations. Weather includes (but is not limited to) thunderstorms, turbulence, icing, precipitation, convective activity, or IFR conditions. Weather affects complexity because pilots are unwilling or unable to fly into certain weather conditions. This causes requests for deviations from procedures and flight paths, as well as other changes.

10. Number of complex aircraft routings. A simple routing is in effect when an aircraft flies along its planned flight path. Complex routings occur when aircraft frequently require manual controller input such as vectors, altitude changes, large course changes, intercepts, etc., or require close monitoring. Complex routings deviate from the normal, and require more attention due to increased chances for conflictions.

11. The extent to which the controller's work is affected by restricted areas, warning areas, and MOAs and their associated activities. Once a restricted area is activated, no flights are allowed in or out of a that airspace. VFR aircraft are allowed to fly in warning areas (over the ocean) or into MOAs, although this is not advisable. These areas reduce the amount of airspace available to controllers, and create obstructions to flight routes. This increases the likelihood of conflictions because aircraft must be rerouted around them. Activities around these airspaces are specialized flights requiring special handling and monitoring.

12. The size of sector airspace. Size of airspace refers to the volume of airspace contained within the lateral and horizontal boundaries of the sector. Size affects complexity because a small sector has less airspace for the controller to utilize in conflict resolution. Size limits the controller's ability to handle traffic volume, and deal with any special conditions, such as weather.

13. The requirement for longitudinal sequencing and spacing. Sequencing refers to prioritizing the order of aircraft for arrival over a fix or destination. Spacing refers to the distance created or required between each aircraft in the sequence. Sequencing and spacing increase the requirement for planning and can increase conflict potential, since they require the streaming of aircraft from several sources into one stream.

14. Adequacy and reliability of radio and radar coverage. Some low sectors lack sufficient radar coverage to detect aircraft below 4000 feet, and some lack the radio coverage needed to enable reliable voice communication in all portions of the sector. When radar coverage is inadequate, the controller must revert to work-intensive, non-radar procedures. Insufficient radio coverage requires the use of alternate communication techniques, such as pilot-to-pilot relays. Loss of radio and radar coverage can result in a need for search-and-rescue operations.

15. Amount of radio frequency congestion. Radio frequency congestion can result from a high number of aircraft in a sector, or can be affected by numerous pilot requests due to turbulence or other factors, such as emergencies. Complexity results because congestion limits the controller's ability to utilize the frequency for issuing instructions to aircraft. Increased probability of separation loss and additional effort to monitor or communicate with aircraft can also result.

2.10 PHASE I GENERAL CONCLUSIONS.

In all phases of this study, there was considerable evidence that controllers within each specialization area agreed on their evaluation of the sectors familiar to them. In the preliminary study, four West Area controllers agreed on their ordering of sectors by complexity, and were generally close on their ratings of similarity of complexity. During factor development, there was a significant correlation between ratings FPLs made on sectors in their areas on an initial set of 24 complexity factors. Controllers were also generally in agreement regarding which sectors were similar in complexity, and each group's judgments could be adequately accounted for by INDSCAL-generated, shared stimulus spaces.

When rating the sectors on a reduced set of 19 Candidate Factors during factor selection, all participants within each specialization area (with the partial exception of 1 Central Area controller) were in agreement. Of the six controllers who rated overall sector complexity, five made similar evaluations of the sectors. The one who did not lacked recent exposure to ATC operations.

In attempting to identify the most effective set of factors for evaluating sector complexity, it was found that 11 Final Factors had significant simple correlations with the Complexity Criterion. Multiple regression revealed that a combination of three of these factors (the Proportion of Complex vs. Direct Aircraft Routings, the Need for Arrival/Departure Sequencing and Spacing, and Radio Frequency Congestion) were strongly related to overall complexity and could presumably be used to estimate the complexity of sectors in the Jacksonville ARTCC. However, the numerous correlations between the 11 Final Factors suggested that they all play some role in sector complexity, and that any theoretical account of the sources of sector complexity should include them. In fact, given the methods used to collect the 19 Candidate Factors, all should be considered as potential variables for future research in this area.

On a practical note, some of the Final Factors could only be measured by controllers trained in the airspace of concern. However, the analysis identified a subset of the these factors, which could be easily evaluated by generalists using sector maps, weather information, and traffic counts. Two out of this set were combined in an equation to adequately account for overall sector complexity. These factors were Spacing and Frequency Congestion.[9]

9 However, it would not be wise to use a small number of factors to assess sector complexity. More reliability would be accomplished using a number of readily measurable variables.

Thus, there was evidence that a workable method could be developed to allow Jacksonville controllers (such as those in the Airspace Planning and Procedures Office) to evaluate sector complexity without having extensive knowledge about all of the sectors in the Center.

The analysis revealed that indices of sector complexity, using the parameters from the multiple regression equation, were closely related to the Complexity Criterion provided by TMU controllers. However, neither of these sets of ratings correlated with FAA complexity, as determined, using the rules contained in FAA Order 7210.46. Although the FAA rating system may not adequately account for sector complexity, further validation work is needed to confirm that the method for evaluating sector complexity generated by this study is more effective.

One purpose of this study was to evaluate direct and indirect techniques for studying ATC knowledge structures. As noted in the introduction, a case can be made for including a technique like MDS, if it is assumed that requesting data in the form of judgments (which rely on an underlying knowledge base) can allow access to information that is not easily verbalized. Experience with both techniques demonstrated that the selected indirect approach was a useful source of candidate sector complexity factors, but was time and labor intensive in its application. The final results showed that MDS did not identify any unique complexity factors; all of the Final Factors were directly suggested by controllers at some point in the study.

Thus, the indirect approach for knowledge elicitation used in this research, did not prove to have any distinct advantages in terms of information yield over directly asking controllers for complexity factors. While the exercise of combining the data from direct and indirect approaches was useful for selecting prominent factors for further analysis, the time and effort required to collect and interpret the MDS data must also be considered. MDS should be used in cases where multiple sources of data are needed, such as to reduce a large list of potential factors by seeking overlapping information from unrelated techniques. In other cases, it may be that direct knowledge-exploration techniques are adequate for the purpose of identifying items, such as sector complexity factors.

For interpretation of MDS results, a statistical, as opposed to subjective, method of interpretation should be employed, unless the experimenters have direct access to SMEs in the target domain. By employing previously gathered sets of ratings in a regression analysis, a statistical method obviates the need for the technical knowledge required for direct interpretation of MDS spaces.

The results of this study are specific to the Jacksonville ARTCC, and may not be fully generalizable to other en route or terminal ATC facilities. It is likely that some of the identified complexity factors are common to many areas, although some, such as certain weather problems, may be unique to particular en route and terminal areas.

Although this study has contributed to the identification of the factors that are important in creating complex airspace, further validation work is needed to confirm these results. Ultimately, a useful tool for evaluating sector complexity will result. Although controllers showed agreement on their ratings of sector complexity, the data revealed that they did not necessarily concur on the relative importance of complexity factors. This finding suggests that individual controllers may respond differently to a given constellation of complexity factors.

Assuming that many of the factors contributing to sector complexity have been delineated, this permits further work on the effects of complexity on controller decision making. Accordingly, this report continues with a description of the Phase II research on controller decision making.

3. PHASE II - DECISION MAKING (PRELIMINARY STUDY).

3.1 INTRODUCTION.

The preliminary decision-making study was designed to relate the findings on sector complexity to controllers' behavior while managing sector traffic. It was assumed that the information collected about sector complexity factors would provide a background against which controller decision-making activities could be analyzed.

3.2 APPROACH.

A simple decision-making model was adopted, based on one documented in an en route ATC training manual (FAA, 1989). This model is diagrammed in figure 6. The model assumes that decision making occurs in four phases: Scanning, Projecting, Planning, and Acting. The Scanning phase involves continuously switching attention between different kinds of visual and auditory data. Visual data are provided by the radar display and flight progress strips, while auditory data are available from radio and telephone communication systems. The research team assumed that an underlying mental representation of the ATC situation directs the switching of controller attention between these sources of data. The team further assumed that the purpose of scanning is to update this mental representation as the basis for detecting potential problems.

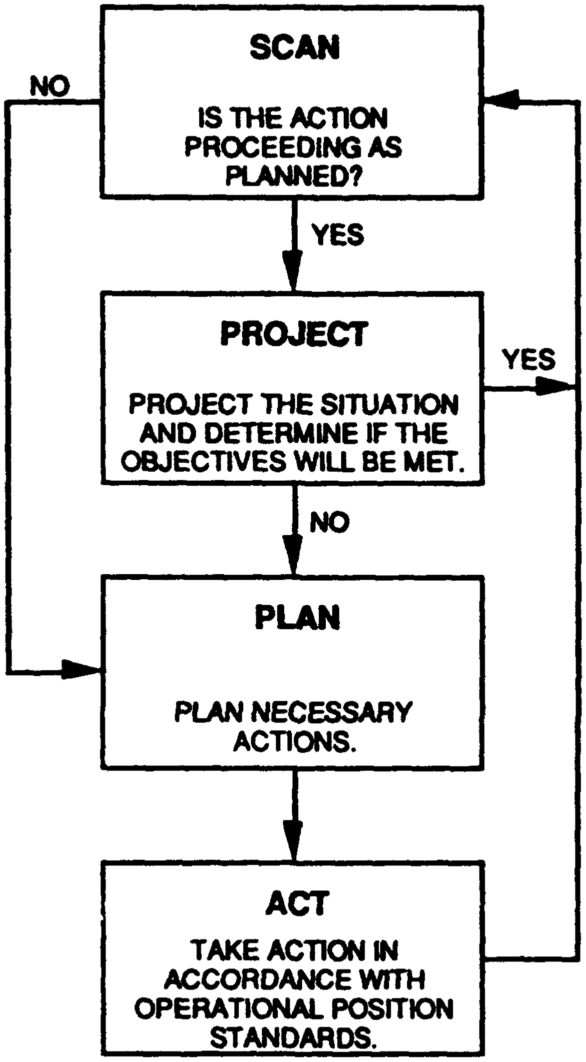

Figure 6. Decision-Making Model

According to the adopted model, upon detecting a potential conflict, the controller Projects the future positions and altitudes of the aircraft concerned, and then assesses the likelihood of the conflict. During the Planning phase, the controller is thought to generate and review the possible solutions to the problem. (An important alternative is recognition of the solution based on past experience, which does not involve generation of all possible solutions.)

The adopted model's Acting phase represents the decision to select and implement a chosen solution. (If the solution is recognized, projecting leads directly to acting.) The Scan-Project-Plan-Act cycle is repeated continuously while the controller is working air traffic. While this model is primarily a heuristic for training purposes, it matches controllers' reports of their decision-making process sufficiently to guide preliminary research. The decision-making study employed time-limited, simulated ATC problems to analyze each stage of this initial decision model.

Approaching the study of controller decision making in this way allowed information to be collected on various aspects of the process. It also permitted consideration of the effects of knowledge structures or sector complexity factors on the three major phases: Problem Analysis (including Scanning and Projecting), Planning, and Acting. It was assumed that the sector complexity factors inherent in each ATC problem might influence controller behavior in observable ways. Measurement of such effects was restricted to a qualitative analysis. At this stage, no comparisons were made between sectors or problems on any objective variables that might be correlates of decision processes.

3.3 METHOD.

3.3.1 Participants.

The initial set of participants included seven FPLs from various specialization areas at the Jacksonville ARTCC. The choice of participants was restricted to supervisory personnel only. Given this participant pool, it was not possible to limit the study to controllers from one specialization area, as had been originally planned. Instead, participants from other areas were included; this allowed comparison of results between areas.

There were three North Area controllers, two from South, and one each from the Central and West Areas. Experience as an FPL ranged from 5 to 17 years. However, none of the participants was working full time as a controller at the time of the study. They were functioning in supervisory or other non-operational positions. All participants but one maintained minimum required ATC currency by controlling traffic a minimum of 16 hours per month.

3.3.2 Apparatus.

The preliminary decision-making study was conducted on a 486 personal computer with a 17-inch color display. TRACON (Wesson, 1988) ATC simulation software was used to create six air traffic problems ranging from low to high complexity (as evaluated using the previously discussed complexity factors) in three of the North Specialization Area sectors. Accurate sector maps and realistic ATC problems were developed with the assistance of a North Area controller. One of these problems was selected and refined for use during the experiment.

Each experimental session took place in the Computer-Based Training Room at the Center. The experimenter collected data and acted as a simulator pilot by entering participants' ATC instructions into the simulator with a keyboard. Sessions were recorded on video and audio tape.

3.3.3 Procedure.

Participants were seated in front of the computer monitor and given an introduction to the experiment. Then a simple air traffic problem was run using a "generic sector" to allow practice with the simulation program. When the participant indicated readiness, a problem was started that had been created for the Florence sector, in the North Specialization Area. The seven aircraft in the problem were allowed to enter the sector and move to a set start point, at which time the simulator was paused. The participant was provided with flight progress strips for each aircraft, and asked whether sufficient information was present to understand the problem and formulate a solution.

A series of questions was reviewed before the problem was restarted. To address Scan and Project (Problem Analysis) issues, participants were first asked to note all pairs of aircraft that might come into conflict, assuming the problem was allowed to run ahead with no controller intervention. Once this was accomplished, the controller estimated a safety risk probability (in percent) with each conflict. Participants were then asked to provide comments and ratings on the importance of data from the radar screen, as opposed to flight strip data, and on the criticality of each category of aircraft information for understanding the problem. (These assessments were made on seven-point scales. It was not feasible to include voice communication as a factor because of limitations imposed by the simulation system.)

Ratings of the problem on each of 13 of the previously-developed complexity factors[10] were requested, and each participant was asked to report familiarity with the sector, and problem, and to estimate the difficulty of the problem (on seven-point scales). The controller responsible for generating the problem was also asked to evaluate its complexity on the same scale, to provide a baseline for comparison.

Each controller was also asked whether the solution to the problem had emerged fully formed, or had been recognized immediately, suggesting recognition-primed decision making (RPD) (Klein, 1989), or whether it had been worked out from first principles. RPD essentially by-passes the generation and evaluation of alternative solutions, going directly from identification of the problem to acting. RPD is characteristic of expert problem solving in naturalistic settings (i.e., outside the laboratory).

The data collected on the Plan portion of the decision-making model included two kinds of predictions made by participants. First, each participant was asked to note (on a horizontal timeline) planned control actions that were intended to solve the problem. These actions were to be predicted as far ahead as would normally be anticipated. Then, a sector map was presented, and participants drew predicted aircraft trajectories as far ahead as they could determine. Different colored pencils were used to distinguish the predicted trajectories for each of the seven aircraft in the problem.

In order to discover how controllers' plans changed during problem solving, the Florence sector problem was paused every 3 minutes (or twice) during each experimental simulation run. At each juncture, participants were asked to point out where they were on their preceding timeline, and to produce a new timeline and map with the time of each pause as a start point. It was assumed that participants would cycle through the Scan-Project-Plan-Act stages of decision making during problem execution, and that stopping the simulation at these points might allow access to changes in their approach to the problem.

The Act part of the decision-making process consisted of the instructions given by participants to the simulated aircraft during the simulation run. Interactions with aircraft were video- and audio-taped. At the end of each session, the experimenter played back the video tape of the session, and asked the participant to describe the points at which the plan changed, and reasons that prompted such deviations.

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10 Some complexity factors were not relevant given the characteristics of the chosen sector, problem, and simulation system.

After data collection was completed, the experimenter reviewed the video tapes, and recorded all ATC actions taken by each participant. The experimenter traced the actual flight paths of the aircraft on a sector map during video tape playback.

3.4 RESULTS.

The results are categorized by the decision-making phase they represented.

3.4.1 Problem Analysis (Scan/Project).

When asked to compare the importance of the radar screen and flight strips for problem analysis, every participant emphasized the screen over the flight strips. The average importance rating for the screen was 6.8 (on a seven point scale). Participant ratings of flight strip importance were lower and more variable (averaging 3.7). One controller commented that the screen provided current aircraft status, while the flight strips were useful for information about the future.

Participants were quite consistent in their indications of the types of information available from each source. The radar screen was relied upon for aircraft identifier (ACID), altitude, heading, and location data, while flight strips provided aircraft type and flight plan. When asked to evaluate the importance of each kind of aircraft data for analyzing the Florence problem, participants consistently mentioned altitude, location, speed, and heading as being critical. Flight plan and aircraft type were also considered useful, but opinions were more varied. ACID was rated least important by most participants, with two notable exceptions.

As is illustrated in table 16, controllers did not agree on the anticipated number or safety risks of potential conflicts in the problem. Participants projected an average of six conflicts (ranging from five to eight). In fact, when the air traffic scenario was run ahead with no controller intervention, two pairs of aircraft lost separation (5 miles horizontal or 1000 feet vertical). Five participants predicted one of these actual conflicts, and six predicted the second, assigning them a priori probabilities ranging from 10 to 100 percent.

Table 16. Predicted and Actual Conflicts
(Actual conflicts in bold, near conflicts in italics).

P	USA1166	**USA352**	USA352	**RACE11**	RACE11	RACE11	RACE11	RACE11	*RACE11*	**TOTAL**
	ACE520	**USA575**	UAL812	**ASE520**	USA833	USA575	UAL812	USA352	*USA1166*	
1	100	100		50	75	100				5
2	10	85		10	15	95	80			6
3	100	95	95		10	95	95	95		7
4	70			100	100	80	80			5
5	100	100	90	50	30		100			6
6	100	100	100	UNK.	UNK.	100	100	100		8
7			100	50	100		100		50	5

The simulated Florence problem had been designed with a set of sector complexity factors in mind. Each participant was asked to rate the problem on a series of 13 factors, and their ratings were compared with those of the Jacksonville ARTCC controller who had designed the problem. The seven participants did not always agree on each factor, as can be seen by the ratings shown in table 18. To gauge agreement with the problem-creator's ratings, product-moment correlations were calculated between all participants' ratings, and the ratings of the controller who designed the problem. Resulting correlation coefficients were moderate (r values ranged between 0.53 and 0.76; all but two were significant at $p < 0.05$).

Before proceeding to describe their plans, the seven participants were asked to make three types of ratings. First, they evaluated their familiarity with the Florence sector airspace, then their familiarity with the simulated Florence problem, and finally the difficulty of the problem (all on seven-point scales). The average rating for sector familiarity was 3.6; average problem familiarity was 5.3, and average problem difficulty was 3.8. However, these averages did not properly reflect the ratings made by this group, given that individual values varied considerably between participants. For sector familiarity and problem familiarity, there was substantial variability. Problem difficulty ratings were more consistent.

3.4.2 Plan.

The planning data were of two types: predicted timelines and predicted flight paths. In order to evaluate the timeline responses, each participant's anticipated instructions were compared with the actual instructions they issued during the simulated problem. Several measures were calculated, as shown in table 18.

Table 17. Sector Complexity Ratings by Problem Designer and Participants

FACTOR	PD	P1	P2	P3	P4	P5	P6	P7	AVG.
MULTIPLE FUNCTIONS	7	5	3	4	6	6	6	7	5.33
HUBBING	7	1	6	7	1	6	6	6	5.33
ARR./DEP. SEQUENCING	7	6	6	7	4	7	6	6	6.00
DEPART/ARRIVING	6	6	7	7	2	2	6	6	5.00
INTERSECTING	5	6	7	7	4	4	5	6	5.50
VOLUME	5	4	7	2	2	3	2	4	3.33
SECTOR SIZE	5	3	4	2	1	5	1	5	3.00
OVERFLYING	4	4	6	1	1	3	7	6	4.00
COMPLEX ROUTINGS	4	1	1	1	2	6	5	5	3.33
MIX	3	4	6	1	2	1	5	5	3.33
MILITARY	3	2	5	1	1	3	1	4	2.50
NO. FACILITIES	1	1	1	1	1	4	1	5	2.17
RESTRICTED AREAS	1	1	1	1	1	3	1	2	1.50

Table 18. Measures of Planning Efficiency

MEASURE	S1	S2	S3	S4	S5	S6	S7
NUMBER PREDICTED	37	36	16	13	19	28	13
NUMBER ACTUAL	25	22	32	21	29	26	31
MATCHES IN FIRST PLAN	17	16	7	5	10	14	5
D-MATCHES	19	19	13	9	16	9	0
I-MATCHES	3	2	3	4	1	10	13
TOTAL MATCHES	22	21	16	13	17	19	13
REPEATS	15	7	0	0	0	2	0
FIRST MATCHES/ACTUAL	68%	73%	22%	24%	34%	54%	16%
MATCHES/ACTUAL	88%	95%	50%	62%	59%	73%	42%
MATCHES/PREDICTED	59%	58%	100%	100%	89%	68%	100%

Number Predicted refers to the total number of actions participants said they would make during the three planning periods (initial, first pause, and second pause). Number Actual was the number of instructions issued to aircraft during the simulated ATC problem. A D-Match was counted when there was a direct pairing of a predicted action with an observed action. An Indirect Match, or I-Match, was counted when there was sufficiently close correlation between predicted and actual to assume that the planned event was ultimately carried out. Total Matches was the sum of D and I matches.

The effectiveness of each participant's predictions was calculated in several ways. First, Matches/Actual (matches from pre-scenario plan divided by total number of instructions issued) reflected how well the participant predicted events during the entire problem at the initial planning stage, before the simulation was started. Matches/Actual was the ratio of all predicted actions (including initial planning and first and second pauses), divided by the total number of actions taken. This indicated participants' effectiveness in planning after gaining experience with the problem. In some cases, they predicted an action more than once. This redundancy was estimated by dividing total matches by total predicted (Matches/Predicted).

The planned flight paths drawn on the sector maps, prior to the start of the problem, were compared to the actual paths followed by the aircraft. In general, participants were able to draw the projected routes of aircraft through to the end of the problem. When comparing the planned and actual flight paths, it was found that the routes planned were very similar to the routes taken, except in the case of two aircraft. In nearly every case, the flight paths of these aircraft varied from the plan. An example of this is shown in figure 7.

Each participant was asked whether the solution to the problem had emerged fully formed (i.e., had been recognized) or had been consciously worked out. Two participants illustrated the extremes in problem solving: One said that the problem had to be worked out completely by hand, while another indicated that the solution was immediately self-evident. However, the other five participants described the problem-solving process as being a combination of starting with self-evident or immediately available ideas, and then thinking them through in terms of the presented situation. For example, one participant commented that initial steps to solve the problem were clear, but later steps had to be worked out.

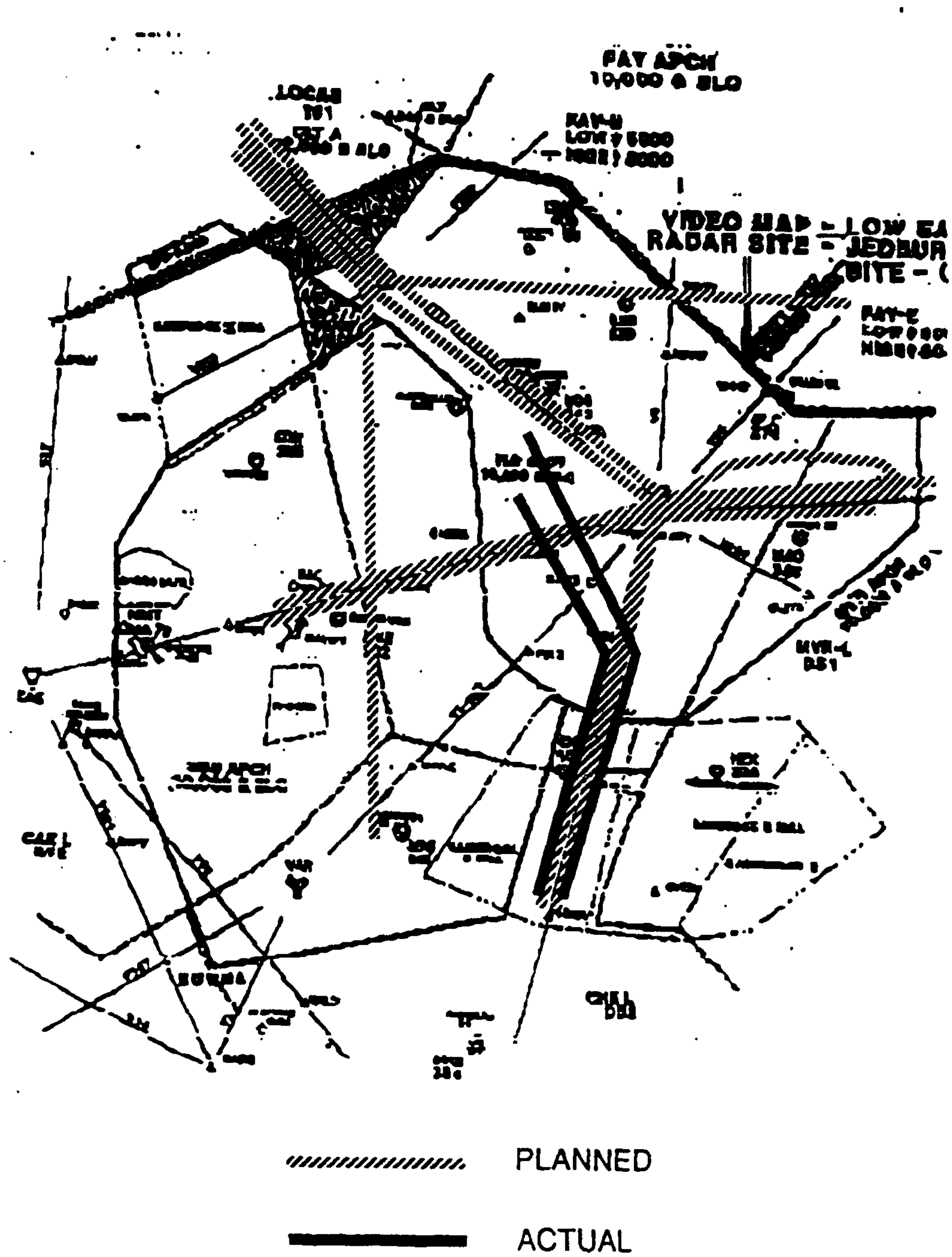

Figure 7. Planned versus Actual Flight Paths
(Only deviations from plan shown)

3.4.3 Act.

The number of steps each participant took to solve the Florence problem varied from 21 to 32 as are shown in table 18. During the pauses in the simulation, and at the time of the video tape review of the problem, participants were asked when and for what reasons they changed their plans. They reported making from one to three changes during the entire problem run. An oft-cited reason for a change in plan was the unpredictable behavior of one of the aircraft, a military flight whose climb rate was not known. Other reasons for plan changes included detection of a conflict, a change in sequencing method, for maintenance of spacing, and unpredicted aircraft paths.

3.5 DISCUSSION.

While reviewing the results, it may be helpful to keep in mind that controllers participating in this experiment came from different areas of the Jacksonville Center, and had varying amounts of ATC experience. This diversity may explain some of the inconsistencies.

3.5.1 Importance of Available Information.

When analyzing the simulated Florence problem, participants stressed the importance of radar screen information. In particular, they looked to the screen for current aircraft status including ACID, altitude, heading, and location. Flight strips provided future information regarding flight plan, and were also relied upon for information on aircraft type. Participants were not given instructions about writing on the flight strips provided to them for the study, and appeared to handle the simulated problem adequately without making notations.

Altitude, location, heading and speed were reported as the most critical pieces of aircraft data. However, there was not consistent agreement on the usefulness of other kinds of data, such as aircraft type. One controller, for example, found aircraft type information to be highly critical, while others did not. This variation in emphasis may reflect differences in controller styles. Some controllers may, for example, use speed controls more frequently in their work, and this may require more information on aircraft performance. Controller style may develop as a function of on-the-job training, i.e., a Developmental may develop a style that resembles the training controller's style.

ACID was rated least important by the majority of participants, but it was rated most important by others. This may have been because of different concepts about the criticality of this information. The primary function of aircraft flight number is to identify the target on the radar screen and the entry on the flight strip. In a sense, it is critical information in this role, but it provides very little data about an aircraft's present or future status. Depending upon one's point of view, ACID could then be either critical or unimportant.

3.5.2 Conflict Potential.

When evaluating conflict potential, study participants were quite conservative, given that only two conflicts would have occurred had the simulated Florence problem been left to run ahead with no intervention. Six conflicts were predicted by at least five of the seven participants, although there was a general lack of consensus about the probability values associated with each conflict. A few participants did not predict either of the conflicts that would actually have occurred.

The variability inherent in the conflict data may have several sources. First, some of the participants were not familiar with the airspace, and this may have made conflict prediction more difficult. It is also not known how far ahead controllers typically look to identify possible problems. Like trying to forecast the weather too far in advance, it may have been unrealistic to ask for conflict predictions too far ahead of a normal "time window." Unfortunately, these data do not provide any information on the dimensions of this window. It is also possible that it was difficult for participants to evaluate conflicts as if no intervention would occur, because controllers do not typically perform such evaluations.

Accordingly, some of the conflict predictions may have been made in the context of the strategy each participant had developed for managing the aircraft, thus adding more variation to the responses. In any event, most of the participants in this experiment were careful to identify any potential risks of conflict. Although most of the predicted risks did not, in reality, represent actual conflicts that would have occurred, such planning no doubt served to focus attention on potential problems until they had been fully evaluated.

3.5.3 Effects of Complexity Factors.

One purpose of this study was to consider the effects of specific sector complexity factors on controller decision making. In the problem evaluation stage, it was of interest to discover whether study participants and the designer of the problem had the same perception of sector complexity. The designer of the simulated Florence problem was a North Area controller. Participants' factor ratings correlated moderately well with the designer's evaluation. For the most obvious factors (Intersecting Airways, Multiple Functions, Proportion of Departing/Arriving Traffic, Airline Hubbing, and Arrival/Departure Sequencing and Spacing), participant ratings varied. The most consistent response was for Sequencing and Spacing.

The overall correlations between participants and the problem designer indicate that most participants perceived the problem in the way it was planned. However, on some of the complexity scales, there was an obvious lack of agreement among the participants. One reason for this could have been the diversity of their backgrounds. Only three of the seven participants were North Area controllers. Thus, differences in experience might have affected the perception and weighting of the sector complexity factors. Another problem could have been the wording of the statements in the rating scale. Perhaps participants did not fully understand each complexity factor.

It also should be recalled that sector complexity factors are not objective qualities of the sector and problem. These factors are subjectively interpreted by controllers who assign their own importance levels to the various factors. These importance levels will affect how factors are perceived. The highest level of agreement was for Arrival/Departure Sequencing and Spacing, perhaps because it was the main focus of the simulated Florence problem and was obvious to all participants.

Although controllers were not asked specifically to discuss their actions, with regard to the complexity factors present in the problem, their planning and problem-solving activities provided information on factor effects. One of the highest rated factors was Multiple Functions (see table 16). Participants had to handle arrivals, a departure, and an overflight. No specific problem-solving actions can be directly connected to this factor in that the plans made and executed could be related to more than one requirement, as discussed below.

The next three most predominant factors in the problem were related to traffic flow to and from airports. (Five out of the total of seven aircraft were flying into the Chesterfield airport, and there was one military departure.) Thus, complexity factors in the problem included Airline Hubbing, Arrival/Departure Sequencing and Spacing, and Number of Departing or Arriving Aircraft (see table 16). Traffic Volume also played a role in terms of the concentration of aircraft along one route.

To summarize, the highest rated complexity factors were all related to the theme of arrivals and departures concentrated in one area. When participants planned their solutions to the simulated problem, their major focus was on how to route all five of the arriving Chesterfield flights so that correct spacing could be created and maintained. The effect on behavior was that aircraft were moved away from their original flight plans in order to achieve this goal, and to reduce the conflict potential posed by the number of intersecting airways, another important complexity factor (see figure 7).

Sector size probably limited the number of complex routings that could be considered. The presence of overflying aircraft provided another reason for maneuvering the arriving aircraft away from their flight plans in order to avoid conflicts. A departing military flight played a significant role in causing participants to deviate from their initial plans; its climb rate was potentially much faster than the commercial aircraft and had to be assessed as the problem progressed.

3.5.4 Sector and Problem Ratings.

Participant judgments were indicative of the differences in familiarity with the simulated Florence sector and problem. As might be expected, the three participants from the North Area were consistent in evaluating the sector and problem as familiar. Other participants gave lower ratings. This is understandable considering that they lacked experience with the North Area airspace. Participant evaluations of problem difficulty were more consistent, averaging 3.8 (on a seven point scale). Perceptions of difficulty and familiarity were not significantly correlated with years of experience.

3.5.5 Planning.

Air traffic controllers are encouraged, during their training, to form a plan for handling air traffic situations. Given the short duration of the simulated problem employed for this study, the first planning session (immediately preceding the start of the problem) was chosen to be the focus of this discussion.

The number of predicted instructions during the first planning period varied from 13 to 37. Some participants (judging by their vocalizations during the planning process) painstakingly planned all anticipated actions, while others plotted their initial moves and then adopted a "wait and see" approach to further actions. Although differences between participants in the number of planned actions may be related to ability, variations also may be attributable to type of decision-making style or to other variables.

Number of predicted instructions had a moderate negative, but non-significant correlation with years of ATC experience ($r = -.52$). This suggests (inconclusively) that increasing ATC experience may be related to a reduction in conscious planning activities. This could be expected given the assumption that skills become more automatic and less accessible to consciousness with extended practice.

Number of actual instructions was much less varied than predicted instructions. The average number of actual instructions was 27. This suggests that, although participants used somewhat different strategies to solve the simulated problem, the number of instructions they actually issued was similar. The number of steps taken appears to be less dependent on between-participant differences. A moderate, but non-significant relationship ($r = .63$) was found between years of experience and number of actual instructions. There was a significant correlation between actual instructions and problem difficulty rating ($r = .78$, $p < .05$). This finding suggests that perception of problem difficulty may be positively related to the number of steps actually taken (as opposed to predicted) to solve it.

The percentage of first matches/actual indicated how well each participant's initial plan matched actions taken during the problem scenario. Effectiveness varied from 16 percent to 73 percent. There was no significant correlation with years of experience, ($r = -.52$, $p > .05$), although the size of the correlation suggests that, given more data, controllers with less experience (or who are younger) might prove to be more successful planners. However, as noted above, a style that is not supportive of conscious planning would also reduce predictive effectiveness. Degree of planning ability was not related to specialization area; North controllers were not any more or less effective than were controllers from other areas.

Although there was no quantitative method available to assess the accuracy of predicted aircraft routes drawn by each participant, it was possible to make visual comparisons. All participants drew aircraft routes for most of the anticipated actions. It appeared that it was easier for some controllers to construct a visual plan in two dimensions, as opposed to developing a verbal list of anticipated instructions. In most cases, actual aircraft routes did not deviate significantly from planned flight paths, except in the case of two aircraft. These aircraft, along with five others, had flight plans which had them crossing over the same fix within a few minutes of each other. For some reason, these two aircraft were given ATC instructions to deviate from their planned routes, perhaps due to unexpected problems with negotiating the other traffic past the common fix.

3.5.6 RPD.

Probing for RPD was limited to a question to each participant regarding how the problem solution was developed. Judging by their reports, five of the seven participants indicated that a basic approach was immediately self-evident. One participant said that the solution had emerged fully formed. From these statements, we can assume that at least some part of the problem solution was recognized, rather than developed from first principles.

Even those participants who rated the problem as highly familiar, however, indicated that some fine tuning was required to complete the solution. Nevertheless, this is in line with Klein's (1989) description of the RPD process. The participant who reported consciously working the problem out, also indicated the lowest degree of familiarity with the sector and problem (one on scale of seven). The other six participants averaged six out of seven when rating problem familiarity. This pattern of results shows some support for RPD. RPD requires familiarity and experience with the problem domain and the problem type. Someone who is unfamiliar and inexperienced cannot be expected to recognize the problem or its solution.

During the enactment of the problem, participants changed their initial plans from one to three times. Reasons for changes appeared to fall within three categories: unanticipated pilot actions, inaccurate projections of aircraft movement, and actions that were not anticipated in the initial plan. The number of changes made by a given participant did not correspond with the effectiveness of their initial plan.

3.6 PHASE II CONCLUSIONS.

The results of this preliminary decision-making study indicate that en route air traffic controllers are much more reliant on information from the radar screen as opposed to flight strip information, with aircraft altitude, location, heading, and speed being the most critical data. While the screen offers data on current status, flight strips are useful for future information. In the limited environment of the simulated ATC problem, it appeared that paper strips were not needed as a mnemonic aid and could be dispensed with altogether, given that flight plan and aircraft type information could be posted on the screen. However, this issue requires more study because only a limited form of electronic strip was visible on the ATC simulator interface.

The controllers in this study were not consistent in evaluating conflict potential, perhaps for reasons inherent in the experiment. However, they generally adopted a conservative approach by identifying more problems than would have actually occurred. This cautious attitude has been identified in another study (Bisseret, 1981) and is a prudent one to adopt in the ATC environment.

Participants' cognizance of the complexities inherent in the sector showed some similarity to those the problem designer had in mind. Differences may have been due to varying levels of familiarity with the problem and sector. It was possible to infer that some of the primary complexity factors, in the sector and problem, influenced controller behavior.

There was ample evidence that the complexity factors present in the problem affected problem-solving behavior. However, it was not always possible to determine exactly which factor a given action was addressing. More detailed verbal reports by participants during viewing of problem video tapes would have been helpful in identifying specific effects.

Effectiveness in problem planning varied between participants as did the accuracy of their first plan. One participant was able to account for 73 percent of actual instructions before starting the problem. Differences in planning may have been due to several factors, including amount of experience and controller style. With more ATC background, conscious planning may give way to a "wait and see" attitude that comes from confidence in well-developed problem-solving skills. More data are required to explore this topic. The number of steps taken to solve the problem increased with perception of problem difficulty.

It appeared that controller participants had less difficulty with reporting their plans in a visual format (as opposed to writing anticipated instructions on a time line). This may support the contention that cognitive activities processed in a primarily visual-spatial modality should be researched using the same format; information may be lost when switching to a verbal output. However, it also should be noted that simpler (two dimensional) information was required to complete the maps (altitude and speed changes were omitted).

There was evidence for RPD in that those participants reporting familiarity with the problem indicated that at least part of the solution emerged without conscious deliberation. This finding would not be particularly surprising if all the participants were from the same area, and had the same level of familiarity with the specific problem. However, the participants were from different areas, and were apparently able to transfer their knowledge automatically. This finding suggests that analogous problems occur in other specialization areas, which is a reasonable possibility. For example, a separation problem in one sector may be similar at some level to a separation problem in another sector; therefore, the solution is probably similar at some level. Thus, one can expect a certain level of ATC expertise and RPD to transfer between areas. The main feature of RPD, that alternatives are not laid out and selected in a parallel, deliberative fashion, but emerge as if by recognition in a serial process, seems to have been in evidence.

Indications that participants cycle through the hypothesized decision-making process (as shown in figure 6) a number of times, even during a short-term problem situation, is shown by their reports that they changed their plans up to three times. Reasons for these changes included unanticipated pilot actions, inaccurate projections of aircraft movement, and actions that were not anticipated in the initial plan.

Further research is needed to validate the findings of this preliminary study and to extend the investigation of controller decision making. Additional techniques should be developed to link decision-making behavior to cognitive structures (i.e., sector complexity factors).

4. CONCLUSIONS.

The focus of Phase I of the reported studies was to examine controller cognitive performance by considering the environment in which the controller works. It was thought that if a clearer understanding of the variables that contribute to sector complexity was established, it would facilitate research on controller cognition and decision making.

To this end, two main approaches (direct and indirect) were used to investigate sector complexity in the Jacksonville ARTCC. This resulted in the development of a set of 19 candidate complexity factors, 11 of which correlated with controller judgments of overall sector complexity. The 19 factors were further refined down to a set of 15. These factors should prove useful in future research efforts where the working environment of the controller must be considered or manipulated in some way. However, it should be noted that these factors were developed at a specific Federal Aviation Administration (FAA) site and so generalizations to other air traffic facilities should be made with caution.

Given the establishment of these complexity factors, it was then possible to complete a preliminary study of controller decision making in Phase II. An experiment was conducted at Jacksonville ARTCC using an Air Traffic Control (ATC) simulator to gather various kinds of data on controller problem solving behaviors. As part of this study, relationships were drawn between the complexity factors evident in the chosen problem and controller actions. It became evident that, in studies of sector complexity and controller decision making, it is not possible to separate sector characteristics from air traffic patterns. These aspects of the controller's environment interact to produce the various types of complexity observed in Phase I.

Although interesting data were collected as part of Phase II, it was evident that further work should be completed to relate complexity factors to controller behaviors. It is not sufficient to know that certain complexity factors exist without investigating their effects on controller decision making, workload, and performance. It is recommended that the studies reported in this document be used as an input for future research in this area.

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APPENDIX A

BRIEF INTRODUCTION TO MULTIDIMENSIONAL SCALING AND PATHFINDER ANALYSIS

MULTIDIMENSIONAL SCALING (MDS).

MDS offers a systematic way to measure and understand the relationships between objects when the underlying dimensions that make them similar or different are not known. MDS is a "scaling technique" that uses direct similarity judgments as input. These judgments are made by participants who use a rating scale to indicate the degree of similarity between the concepts or objects of interest. Those making these judgments do not need a conscious knowledge of the attributes of the objects they are comparing (i.e., what makes them similar or different). Their ratings indirectly reflect their knowledge about the stimuli, and MDS can display the results in a spatial map.

MDS processes the numbers generated from people's judgments, and prints out a map (such as shown in figure A1) that represents objects judged as similar to each other as points close together in space. Objects judged as dissimilar are represented as points distant from one another. The objects' interrelationships may best be explained by only a single dimension. However, two or more dimensions are often generated. The MDS process indicates which number of dimensions fits the data best by creating various statistical measures. Once the MDS "space" has been built, it is then up to the experimenter, with help from the original judges or other SMEs, to determine why certain objects or concepts are seen as similar, and why others are perceived to be different.

Figure A1 shows a possible MDS solution for similarity judgments between aviation concepts. Each dimension of the MDS graph represents one possible underlying factor that defines relationships between the concepts. In this example, the horizontal dimension could be related to an air traffic (ground) versus aircraft (airborne) factor, and might be called "location." The vertical dimension could be related to quantities (altitude) as opposed to equipment, and might be named "concreteness." As can be seen, a certain amount of subjective judgment enters the equation to produce the final result. However, if SMEs are used to aid in this process, valuable insights can be gained into the relationships between concepts or objects.

PATHFINDER ANALYSIS.

Pathfinder is a mathematical procedure that uses the same "distance data" employed by MDS, but generates a different spatial map of the data. Distance data are usually similarity ratings, which imply

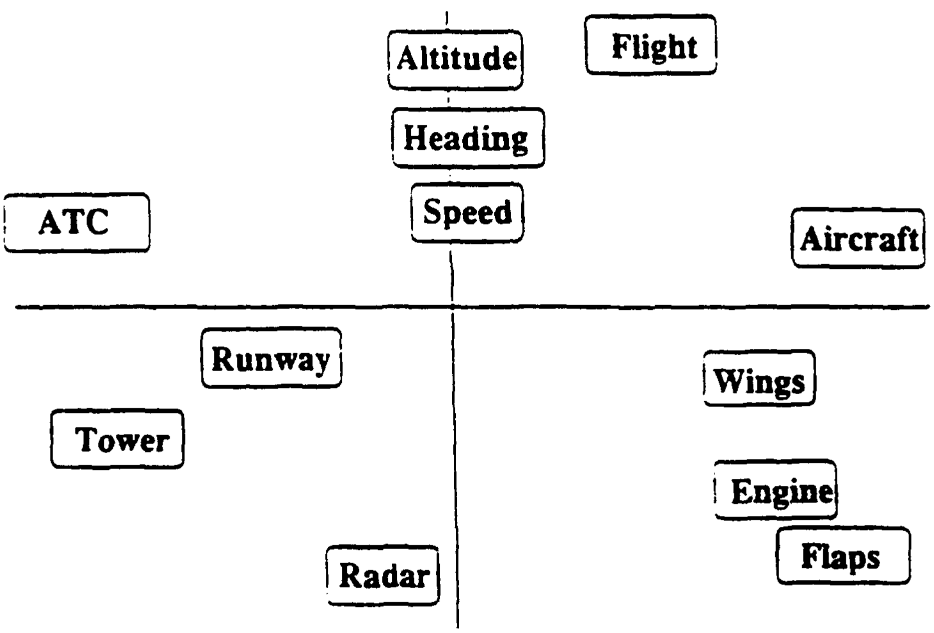

Figure A1. A Hypothetical MDS Result for Aviation Concepts

the "psychological" distance or similarity between concepts and terms. A Pathfinder network consists of a set of concepts and links that directly connect pairs of concepts that are highly related. If Pathfinder has tapped the organization of the participant's knowledge, the resulting graph should represent the basic organization of existing elements, based on an individual's experience.

For example, a Pathfinder network could be derived from the same set of similarity judgments about aviation concepts. A network that displayed the result might look like figure A2. Each concept's relationship to each other is displayed. If the commonalities between concepts are not known, a Pathfinder network can display them. However, as with MDS, it is then up to the user to define the nature of the links between the concepts. While MDS tends to offer general information about a set of concepts, Pathfinder can give a more detailed look at their interrelationships. For example, figure A2 shows three clusters of concepts: aircraft parameters (altitude, heading, and speed), airport concepts (runway, ATC, radar, and tower), and aircraft parts (flaps, wings, engine). The length of the link lines between the concepts demonstrates the degree of relationship (shorter is more similar or more closely related).

MDS and Pathfinder offer mathematically-based methods to look for hidden or unknown relationships between a large set of objects. These techniques can help uncover information that might not be immediately obvious to those familiar with the subject matter.

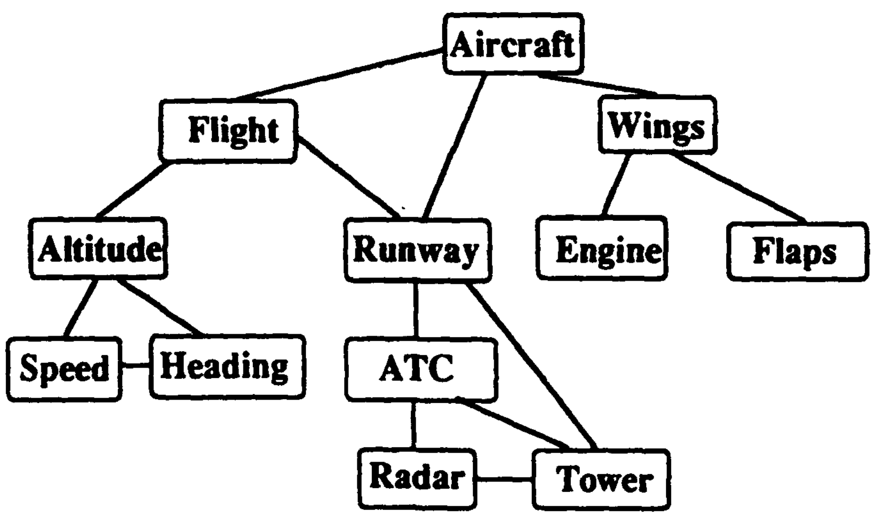

Figure A2. A Hypothetical Pathfinder Network

APPENDIX B

MDS RESULTS AND INTERPRETATIONS FOR SPECIALIZATION AREAS (MAIN STUDY)

NORTH SPECIALIZATION AREA.

The Kendall correlation for the North Area complexity similarity judgments was $\chi^2(35, N = 5) = 101.42$, $p = .0000$, indicating a significant level of agreement between FPLs about which pairs of sectors were similar in complexity.

Stress for the overall two dimensional solution was 0.20, and amount of variance accounted for in the original proximity matrix was 0.66. Stress and R^2 for the five participants were:

Participant	Stress	R^2
1	0.20	0.66
2	0.20	0.67
3	0.21	0.64
4	0.22	0.62
5	0.19	0.71

The shared stimulus space accounted for a moderate amount of variance for all participants. The stimulus space for the five North controllers is shown in figure B1. Dimension one related to radio frequency congestion, and dimension two organized sectors by how difficult they were to manage as traffic density increased. All five of the participants emphasized the two dimensions about equally (see figure B2).

SOUTH SPECIALIZATION AREA.

The Kendall correlation for the South Area complexity similarity judgments was $\chi^2(20, N = 5) = 47.95$, $p = .0004$, indicating a significant level of agreement about which pairs of sectors were similar in complexity.

Stress for the overall two dimensional solution was 0.20, and amount of variance accounted for in the original proximity matrix was 0.75. Obtained stress and R^2 values were as follows:

Participant	Stress	R^2
1	0.25	0.65
2	0.05	0.99
3	0.24	0.63
4	0.20	0.76
5	0.20	0.73

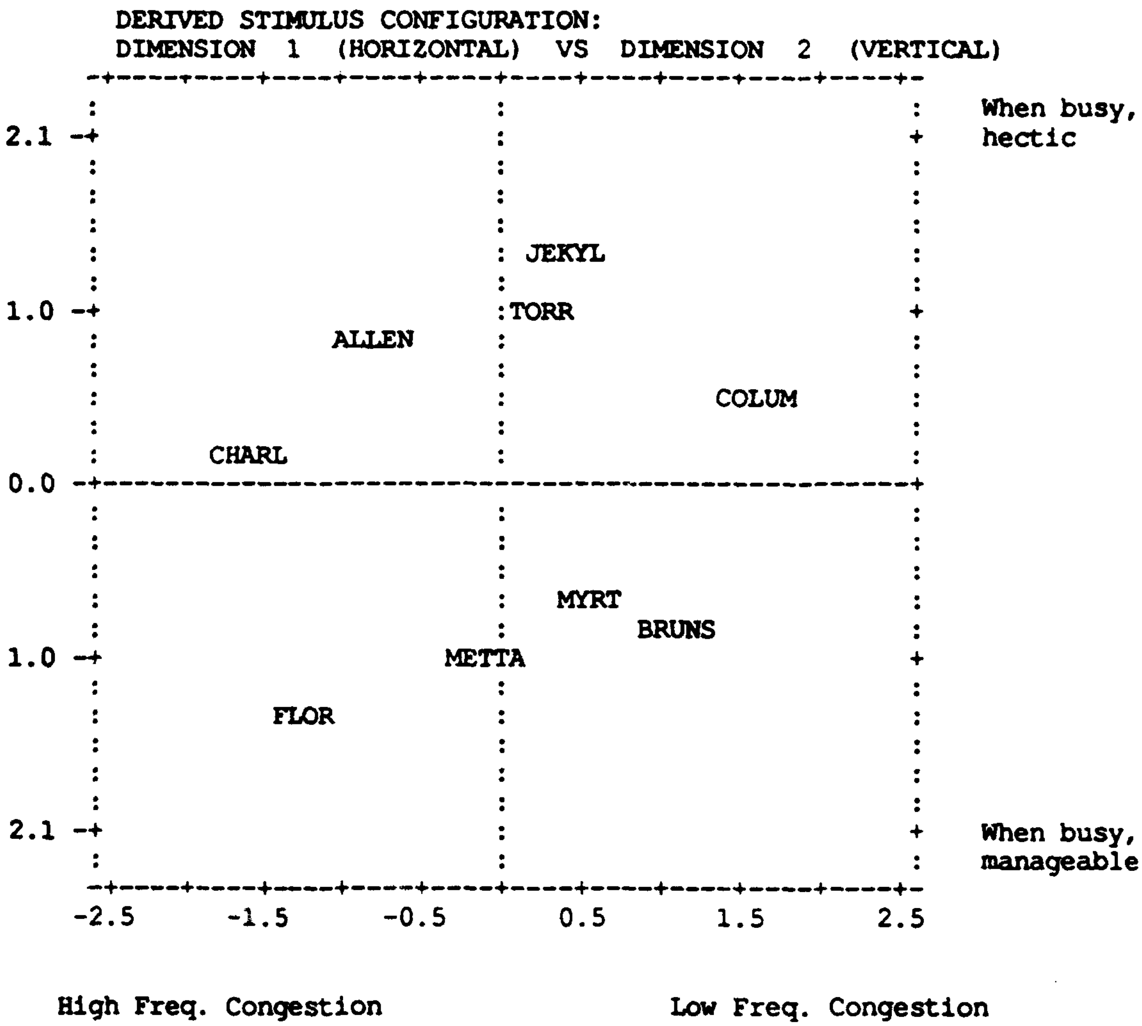

FIGURE B1. MDS STIMULUS SPACE FOR THE NORTH SPECIALIZATION AREA

DERIVED PARTICIPANT WEIGHTS:
DIMENSION 1 (HORIZONTAL) VS DIMENSION 2 (VERTICAL)

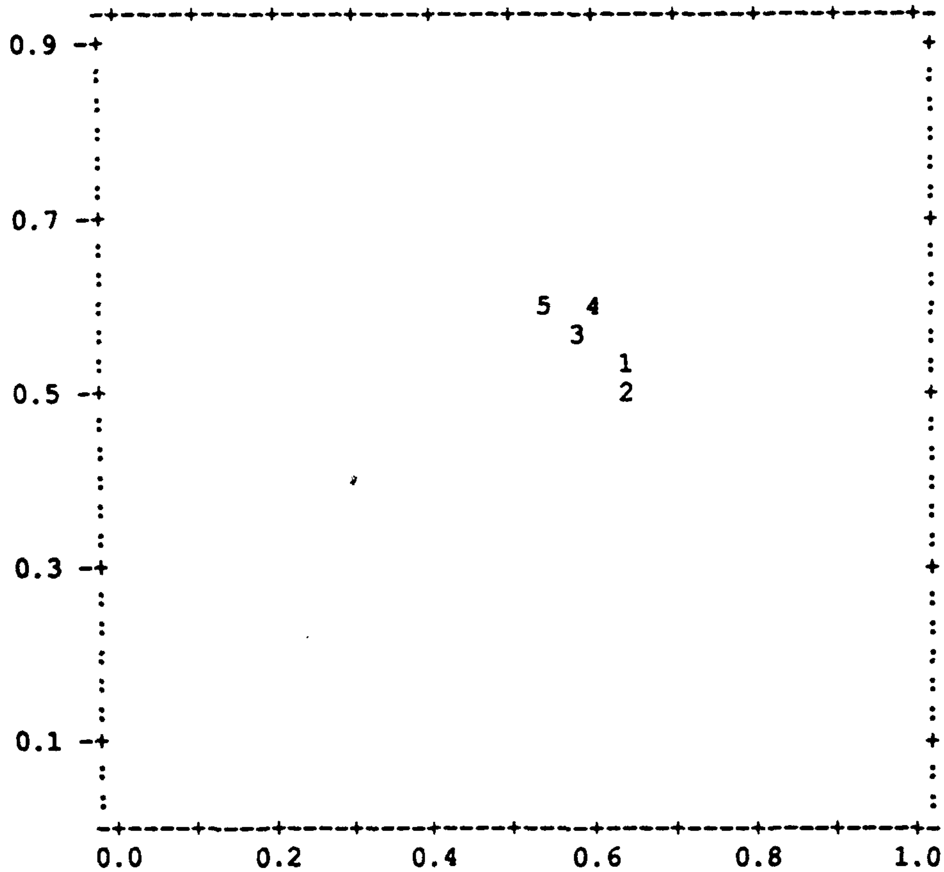

FIGURE B2. PARTICIPANT WEIGHTS FOR NORTH SPECIALIZATION AREA.

As shown in figure B3, the shared stimulus space accounted for a moderate to high amount of variance for individual participants. Dimension one had to do with volume and flow of traffic (arrivals/departures versus overflights), and dimension two was defined by whether a sector mainly had non-professional pilots lying under Visual Flight Rules (VFR) or professional pilots flying under Instrument Flight Rules (IFR). The weight space (figure B4) for the South controllers reflected diversity in the use of the two dimensions. Two participants emphasized the VFR vs. IFR dimension, while the other three used the traffic volume/flow dimension, with participant 2 placing exclusive emphasis on this dimension.

EAST SPECIALIZATION AREA.

The Kendall correlation for the East Area controllers' complexity similarity judgments was $\chi^2(27, N = 5) = 38.99$, $p = .0635$, indicating only a marginal level of agreement about which pairs of sectors were similar in complexity. Stress for the two dimensional solution was 0.22, and amount of variance accounted for in the original proximity matrix was 0.68. The following values were obtained for stress and R^2:

Participant	Stress	R^2
1	0.23	0.60
2	0.21	0.73
3	0.28	0.50
4	0.13	0.92
5	0.25	0.65

The shared stimulus space accounted for a moderate amount of variance for individual participants. Participant 3's judgments, however, were not very well represented.

The stimulus space for the five East controllers is shown in figure B5. Interpretation of the dimensions was difficult, even with the assistance of the Jacksonville ARTCC controllers. The only dimension that emerged was diagonal, and related to sectors with one-way, as opposed to crossing, traffic.

The weight space (figure B6) was difficult to interpret given that it was not possible to name the vertical and horizontal dimensions in the stimulus space. The graph shows, however, that only one participant used both dimensions equally, while the others placed more emphasis on dimension one or two.

WEST SPECIALIZATION AREA.

The Kendall correlation for the West Area complexity similarity judgments was $\chi^2(20, N = 5) = 36.16$, $p = .0147$, indicating a significant level of agreement about which pairs of sectors were similar in complexity.

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          DERIVED STIMULUS CONFIGURATION:
          DIMENSION  1  (HORIZONTAL)  VS  DIMENSION  2  (VERTICAL)
        -+----+----+----+----+----+----+----+----+----+----+-
         :                         :                         :  High Volume
  2.1  -+                          :                         +  Arrival/Departure
         :                         :                         :
         :                         :                         :
         :                         :     ST.AUG              :
         :                         :                         :
         :                         :                         :
  1.0  -+                          :                         +
         :          GAINSVL        :                         :
         :                         :                         :
         :                         :                         :
         :                         :                         :
         :           TAYL          :                         :
  0.0  -+-----------------------------------------------------+
         :                         :       GRNCOV            :
         :          SILSPGS        :       ST.JOHNS          :
         :                         :                         :
         :                         :                         :
         :                         :                         :
 -1.0  -+                          :                         +
         :                         :                         :
         :                         :                         :
         :                         :                         :
         :                         :                         :
         :                         :   KEYSTN                :
 -2.1  -+                          :                         +  Low Volume
         :                         :                         :  Overflights
        -+----+----+----+----+----+----+----+----+----+----+-
       -2.5      -1.5      -0.5       0.5       1.5       2.5

        VFR                                             No VFR
        No Prof. Pilots                                 Prof. Pilots
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FIGURE B3. MDS STIMULUS SPACE FOR THE SOUTH SPECIALIZATION AREA

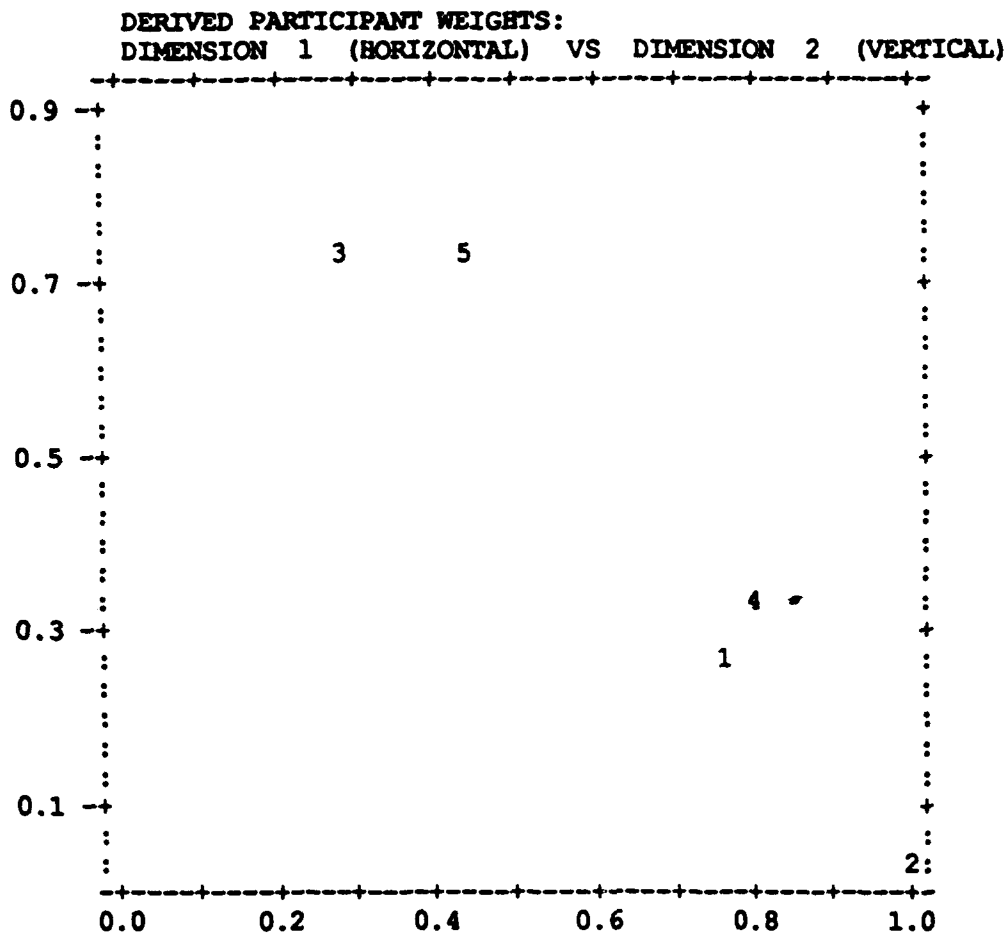

FIGURE B4. PARTICIPANT WEIGHTS FOR SOUTH SPECIALIZATION AREA.

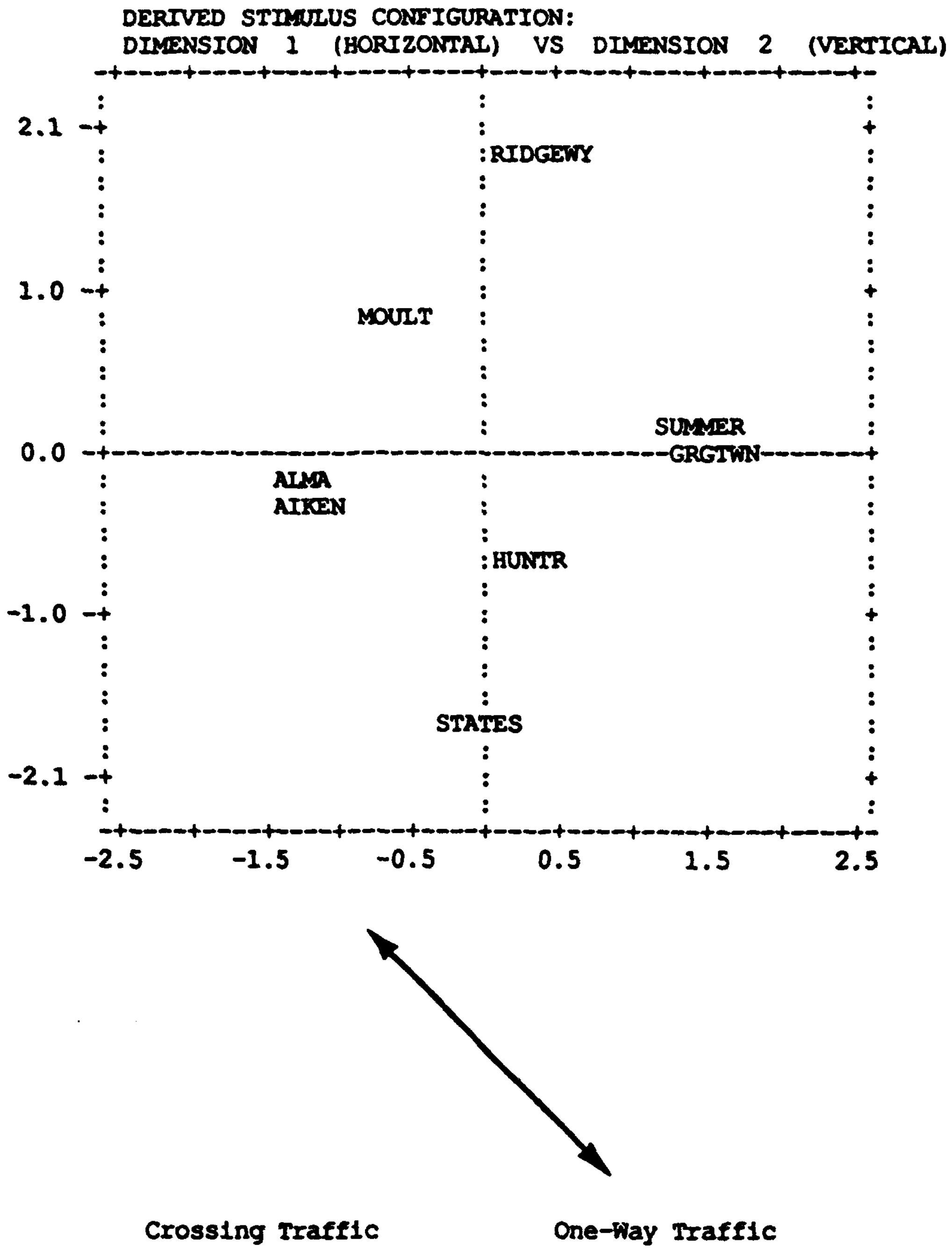

FIGURE B5. MDS STIMULUS SPACE FOR THE EAST SPECIALIZATION AREA

DERIVED PARTICIPANT WEIGHTS:
DIMENSION 1 (HORIZONTAL) VS DIMENSION 2 (VERTICAL)

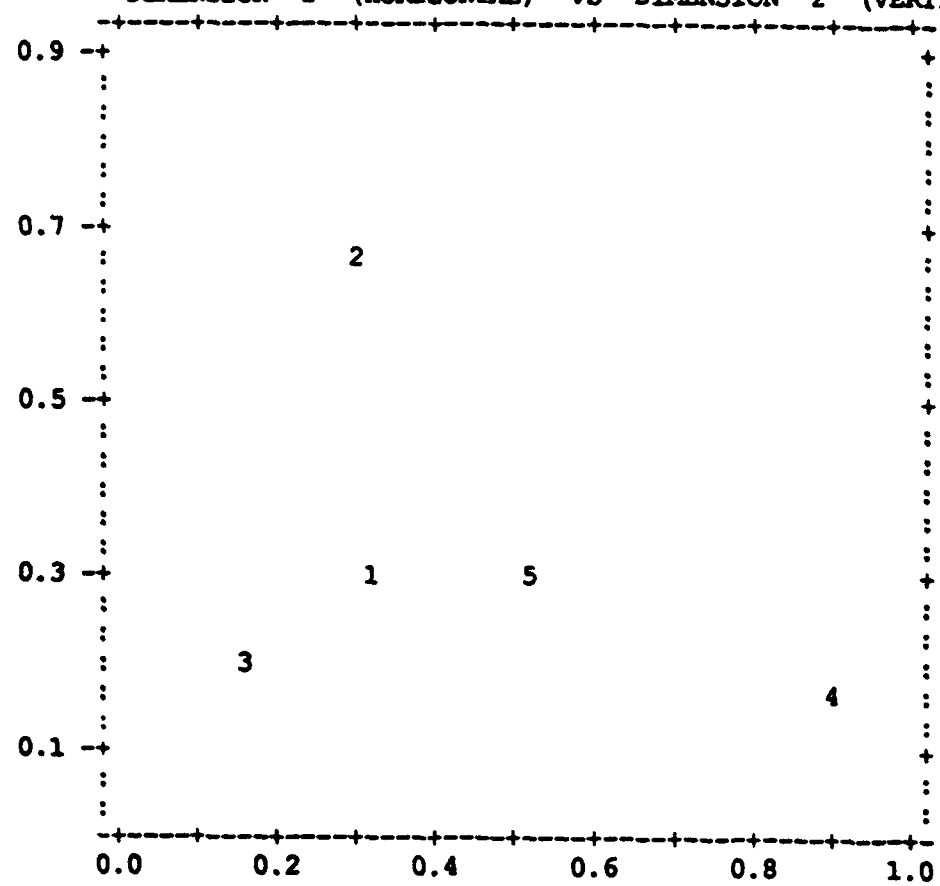

FIGURE B6. PARTICIPANT WEIGHTS FOR EAST SPECIALIZATION AREA.

Stress for the two-dimensional solution was 0.21, and the amount of variance accounted for in the original proximity matrix was 0.67. Stress and R^2 values were as follows:

Participant	Stress	R^2
1	.25	.66
2	.30	.24
3	.10	.96
4	.18	.76
5	.17	.76

The stimulus space accounted for a moderate to high degree of variance for all but one of the West FPLs. Participant 2's data obtained a low R^2 value, indicating that this person's judgments did not correspond well with the others.

The stimulus space for the five West controllers is shown in figure B7. Dimension one represented volume of traffic and number of military flights. Dimension two was oriented around the level of traffic (altitude, overflights versus arrivals/departures) and the presence of VFR traffic.

Weight-space results (figure B8) showed a considerable degree of variability between participants in their emphasis on each of the two dimensions. Participants 1 and 3 based their similarity ratings on traffic volume, including military traffic. Participants 2 and 5 based their ratings on traffic level and presence of VFR aircraft. Participant 4 used both dimensions when making similarity judgments.

CENTRAL SPECIALIZATION AREA.

The Kendall correlation for the Central Area complexity similarity judgments was $\chi^2(20, N = 5) = 41.58$, $p = 0.0031$, indicating a significant level of agreement about which pairs of sectors were similar in complexity.

Stress for the two-dimensional solution was 0.23, and the amount of variance accounted for in the original proximity matrix was 0.73. Stress and R^2 values were as follows:

Participant	Stress	R^2
1	0.14	0.86
2	0.29	0.65
3	0.28	0.54
4	0.22	0.85
5	0.18	0.77

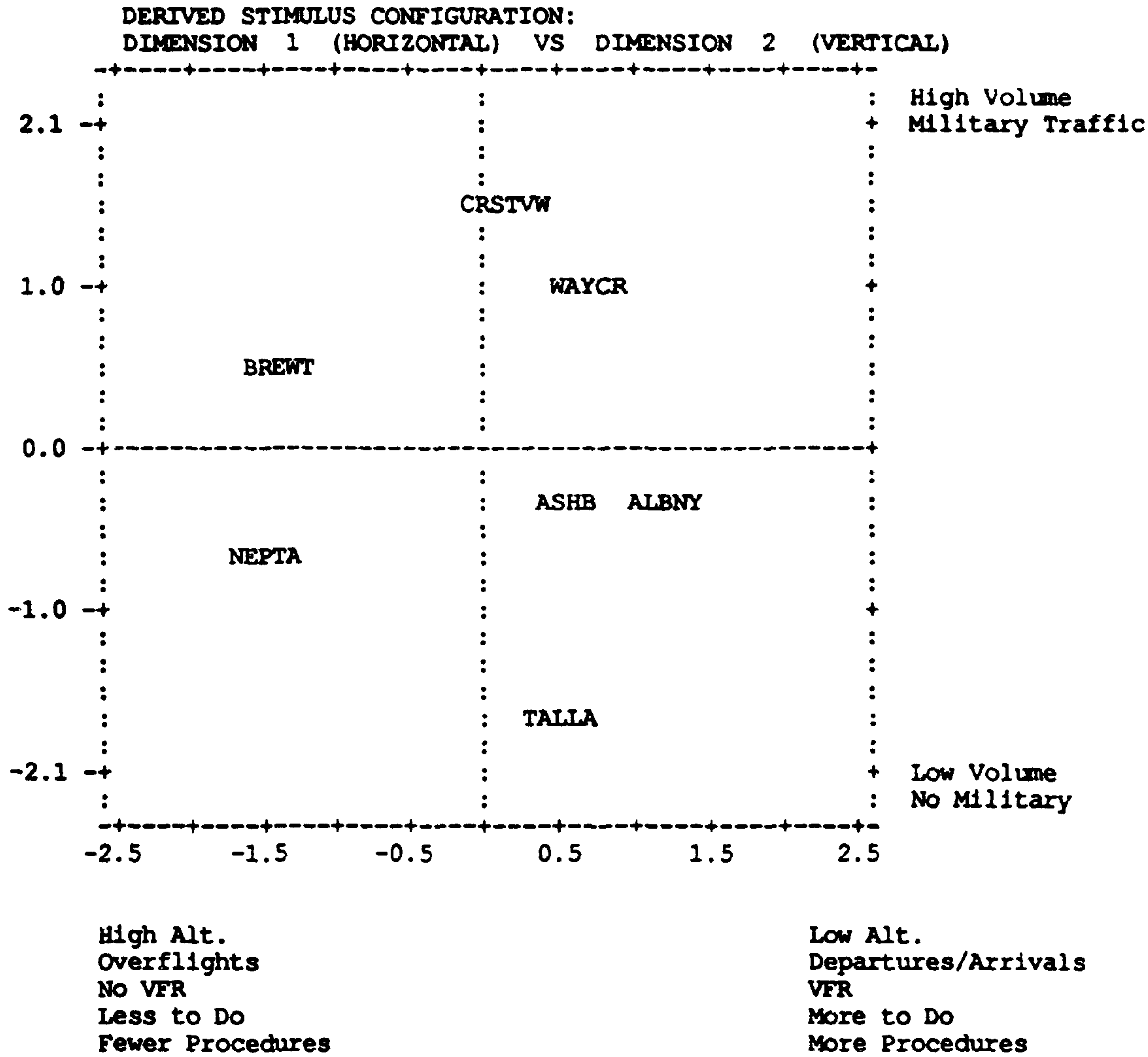

FIGURE B7. MDS STIMULUS SPACE FOR THE WEST
SPECIALIZATION AREA

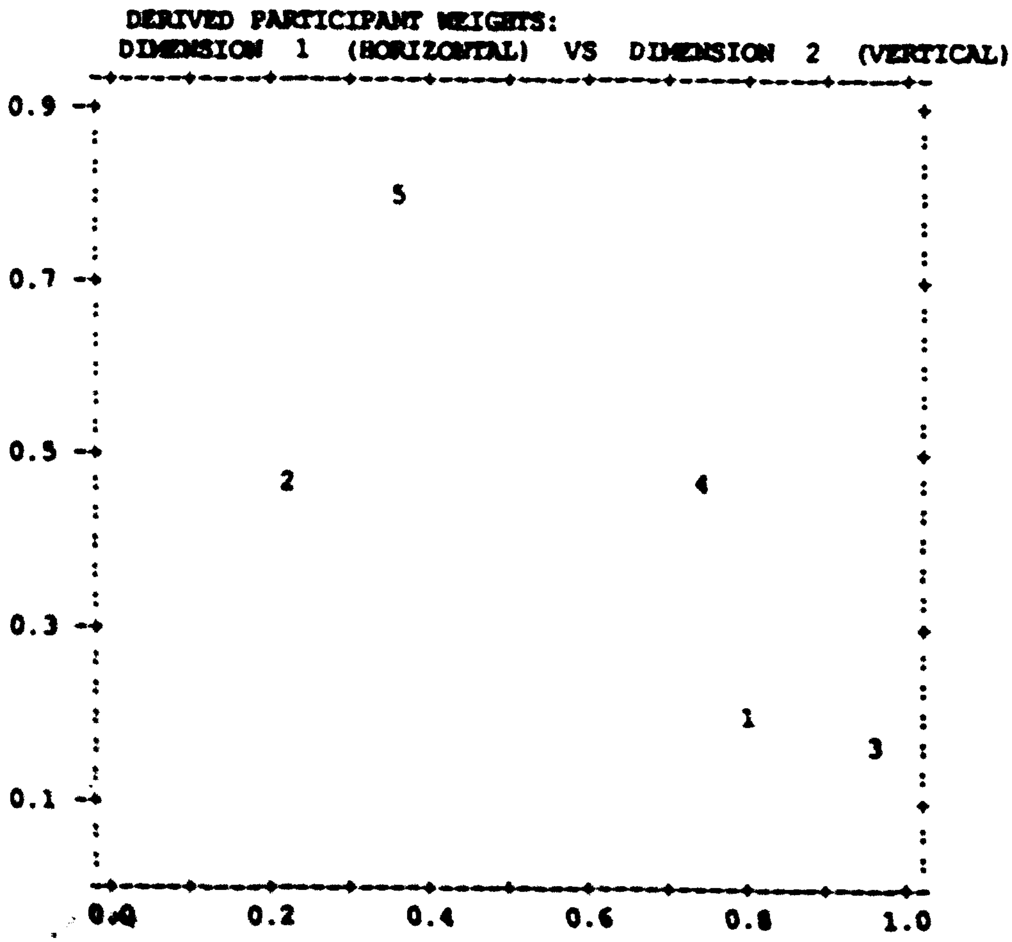

FIGURE B8. PARTICIPANT WEIGHTS FOR WEST SPECIALIZATION AREA.

The shared stimulus space accounted for a moderate to high amount of variance for individual participants. The stimulus space for the five Central controllers is shown in figure B9. Dimension one was related to the amount of coordination and number of functions required in a sector. Dimension two separated sectors with a large proportion of overflights as opposed to climbing and descending traffic.

Two participants used both dimensions about equally in their judgments (figure B10). Participants 2 and 4, however, were more extreme in their use of the dimensions, respectively emphasizing coordination or type of traffic almost exclusively.

DEVELOPMENTALS (EAST SPECIALIZATION AREA).

The Kendall correlation for the complexity similarity judgments made by Developmentals (i.e., controller trainees) from the East Area was $\chi^2(27, N = 5) = 75.55$, $p = .0000$, indicating a significant level of agreement about which pairs of sectors were similar in complexity.

Stress for the two-dimensional solution was 0.23, and the amount of variance accounted for in the original proximity matrix was .78. Stress and R^2 values were as follows:

Participant	Stress	R^2
1	0.41	0.29
2	0.16	0.91
3	0.06	0.98
4	0.25	0.73
5	0.06	0.99

The shared stimulus space accounted for a low to high amount of variance for individual participants (figure B11). Participant 1's responses were not well represented. Dimension one described sectors in terms of their east-west orientation and direction of traffic, while dimension two was concerned with size of airspace and sector boundaries.

The weight space for this group show (figure B12) some divergence in participants' use of the dimensions. Three participants weighted the two dimensions about equally, while two others placed most emphasis on only the first or second dimension. There were some similarities in the knowledge structures of East controllers and East Developmentals. Some pairs of sectors were viewed as nearly identical by both groups.

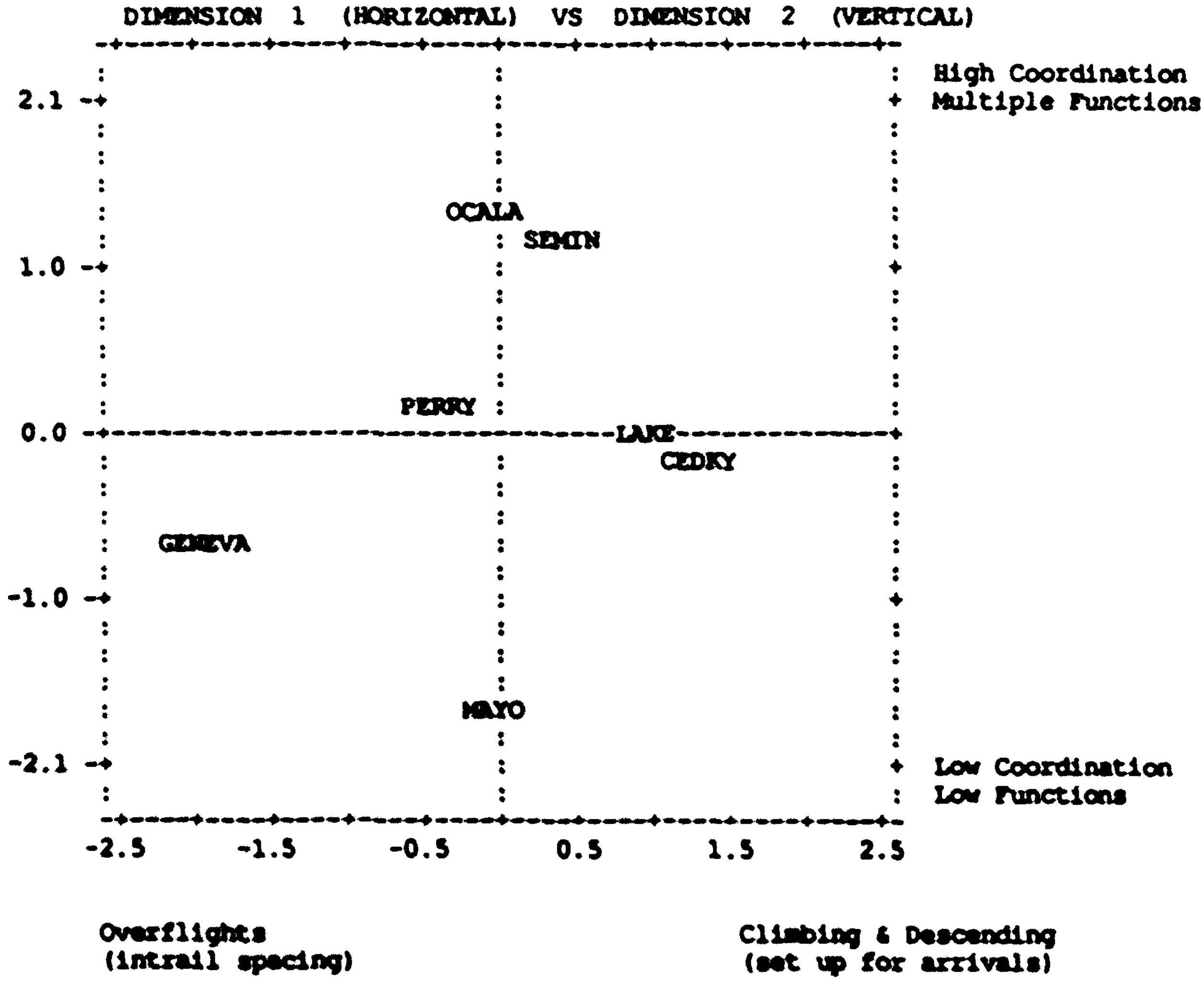

FIGURE B9. MDS STIMULUS SPACE FOR THE CENTRAL SPECIALIZATION AREA

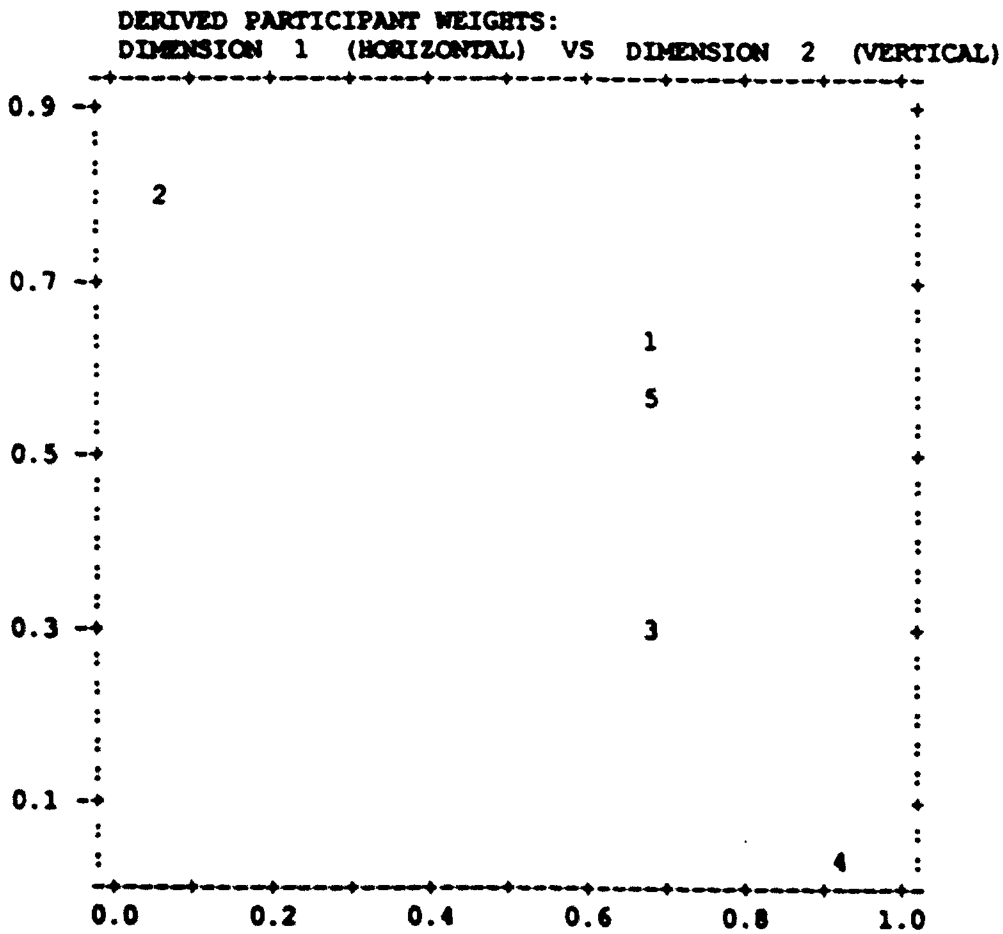

FIGURE B10. PARTICIPANT WEIGHTS FOR CENTRAL SPECIALIZATION AREA.

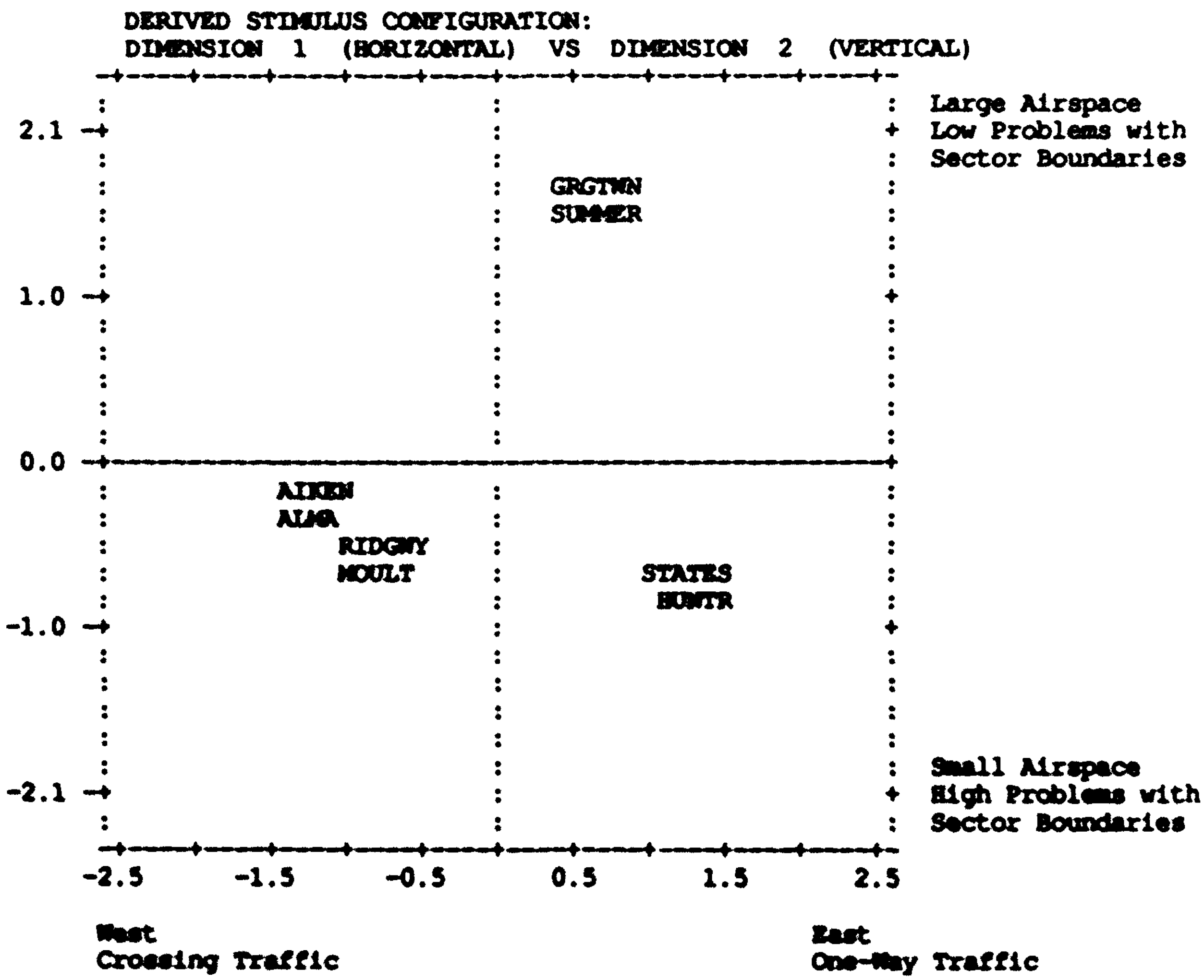

FIGURE B11. MDS STIMULUS SPACE FOR DEVELOPMENTALS
(EAST SPECIALIZATION AREA)

DERIVED PARTICIPANT WEIGHTS:
DIMENSION 1 (HORIZONTAL) VS DIMENSION 2 (VERTICAL)

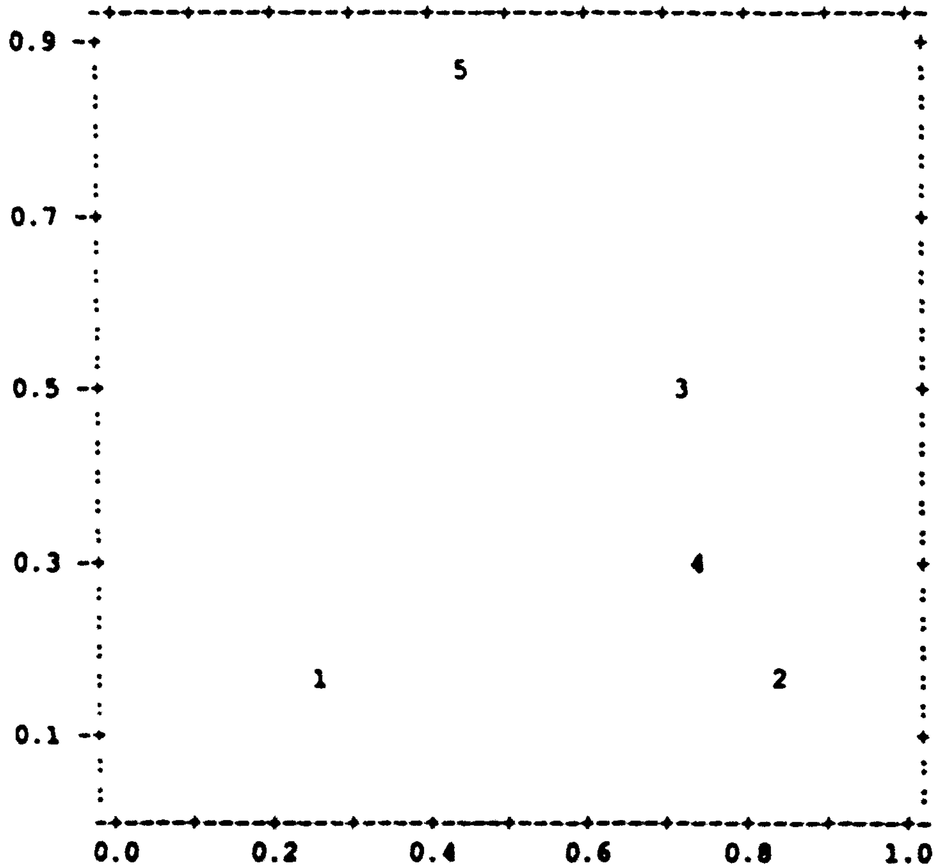

FIGURE B12. PARTICIPANT WEIGHTS FOR DEVELOPMENTALS
(EAST SPECIALIZATION AREA).

AIRSPACE PROCEDURES SPECIALISTS (APSs) AND TRAFFIC MANAGEMENT UNIT (TMU).

The best fitting MDS space for the APSs was two dimensional, with average stress = 0.19 and R^2 = 0.84. INDSCAL's common stimulus and weight spaces for the APSs is shown in figures B13 and B14. Obtained values for stress and R^2 were as follows for Airspace Procedure participants:

Participant	Stress	R^2
1	0.14	0.91
2	0.20	0.85
3	0.21	0.76

Only one participant used both dimensions equally, while the others placed more emphasis on dimension one or two.

For the TMU staff, the MDS space was three dimensional with average stress = 0.19 and R^2 = 0.80 (see figures B15, through B20). Values for the individual TMU participants are shown below:

Participant	Stress	R^2
1	0.20	0.78
2	0.19	0.60
3	0.19	0.85

Participant 1 primarily used dimension two; participant 2 used all three dimensions approximately equally (and had the lowest weirdness); and participant 3 stressed dimension one.

The larger number of sectors in the Airspace Procedures and TMU data sets supported the use of a statistical approach to assist with the interpretation of these stimulus spaces. There was also an interest in contrasting such a procedure with the more subjective method used with the FPL data. The method in question involved mapping known quantities (in this case, the previously gathered ratings of sector characteristics) or "property vectors" onto each space using multiple regression (Kruskal and Wish, 1988). This would result in a set of complexity factors, similar to that derived for the specialization area MDS data using manual methods.

The property vectors generated, using this technique, are similar to the dimensions created by the MDS analysis, and plotted on the MDS graphs. However, they may not be identical to them and may be at different angles. They are plotted to result in the most efficient statistical "fit" to the data.

DERIVED STIMULUS CONFIGURATION:
DIMENSION 1 (HORIZONTAL) VS DIMENSION 2 (VERTICAL)

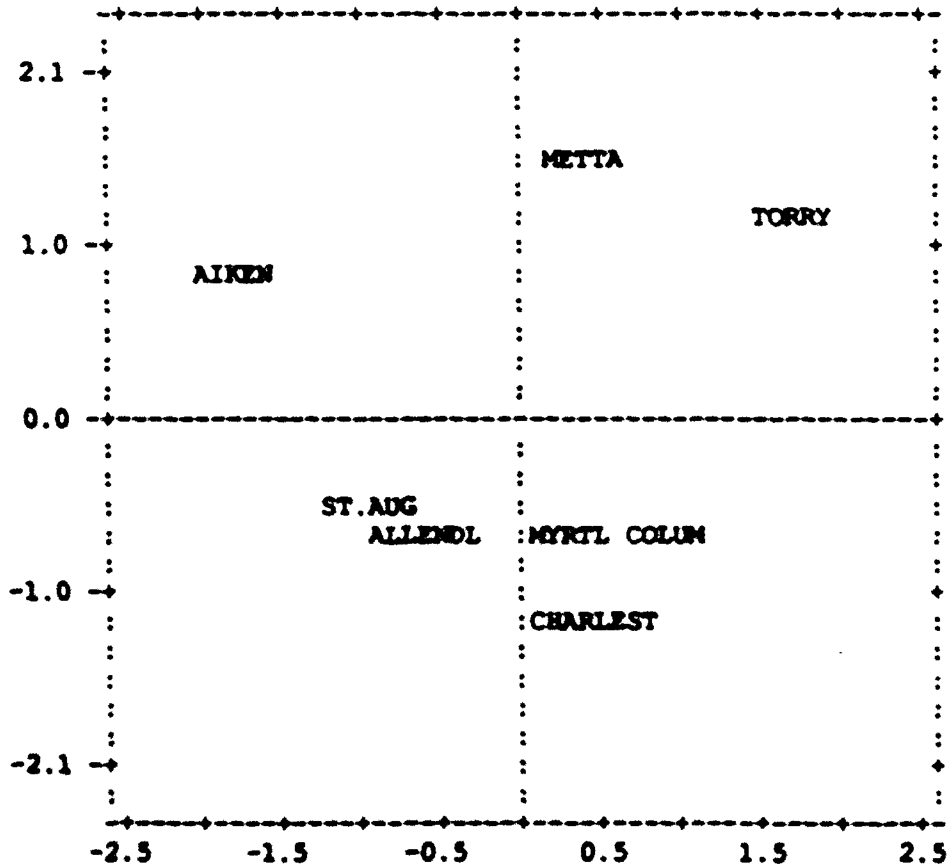

FIGURE B13. MDS STIMULUS SPACE FOR AIRSPACE PROCEDURES SPECIALISTS.

DERIVED PARTICIPANT WEIGHTS:
DIMENSION 1 (HORIZONTAL) VS DIMENSION 2 (VERTICAL)

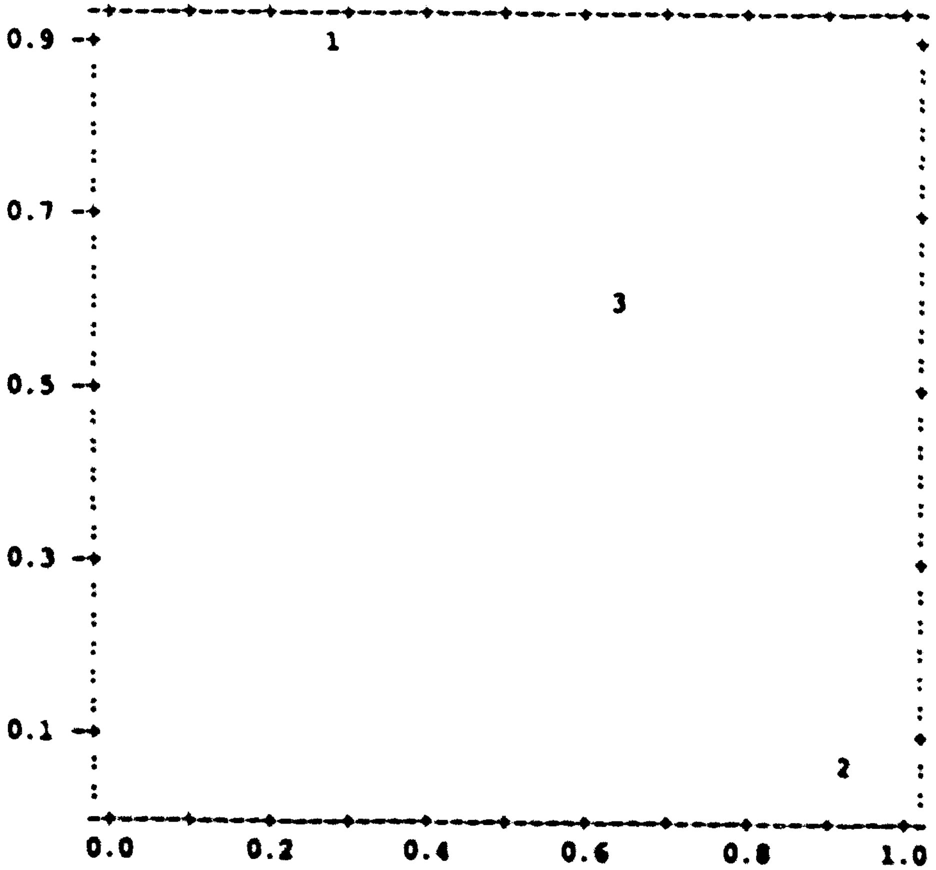

FIGURE B14. WEIGHT SPACE FOR APS PARTICIPANTS.

DERIVED STIMULUS CONFIGURATION:
DIMENSION 1 (HORIZONTAL) VS DIMENSION 2 (VERTICAL)

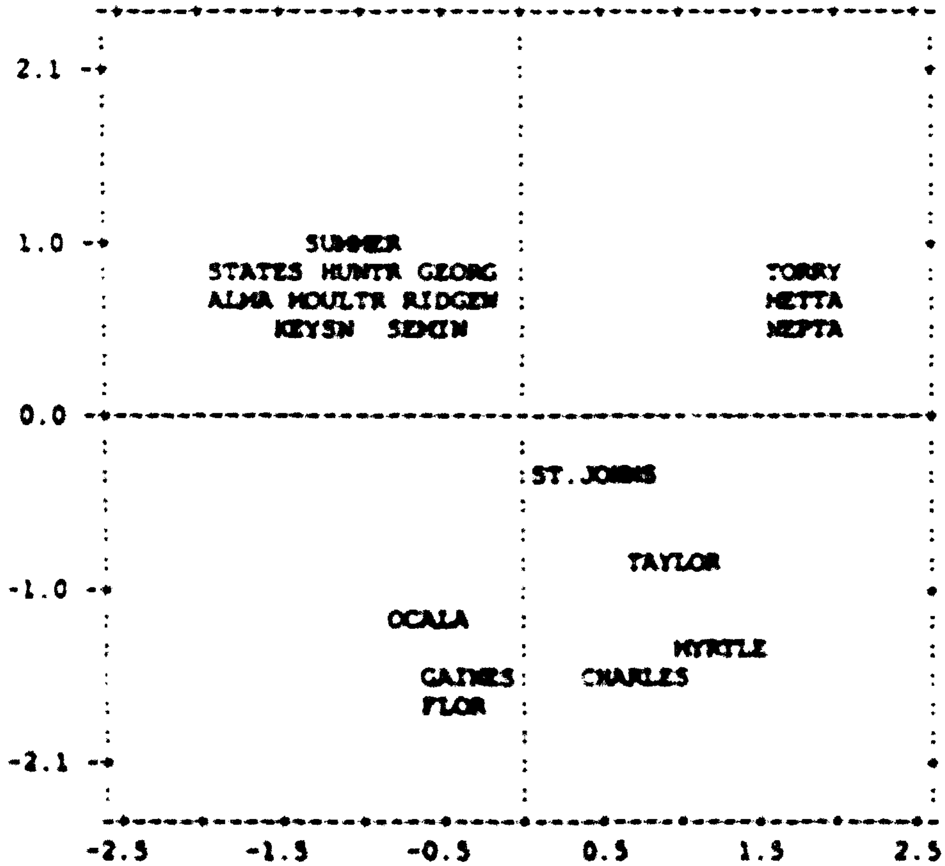

FIGURE B15. TWO DIMENSIONS, ONE VERSUS TWO

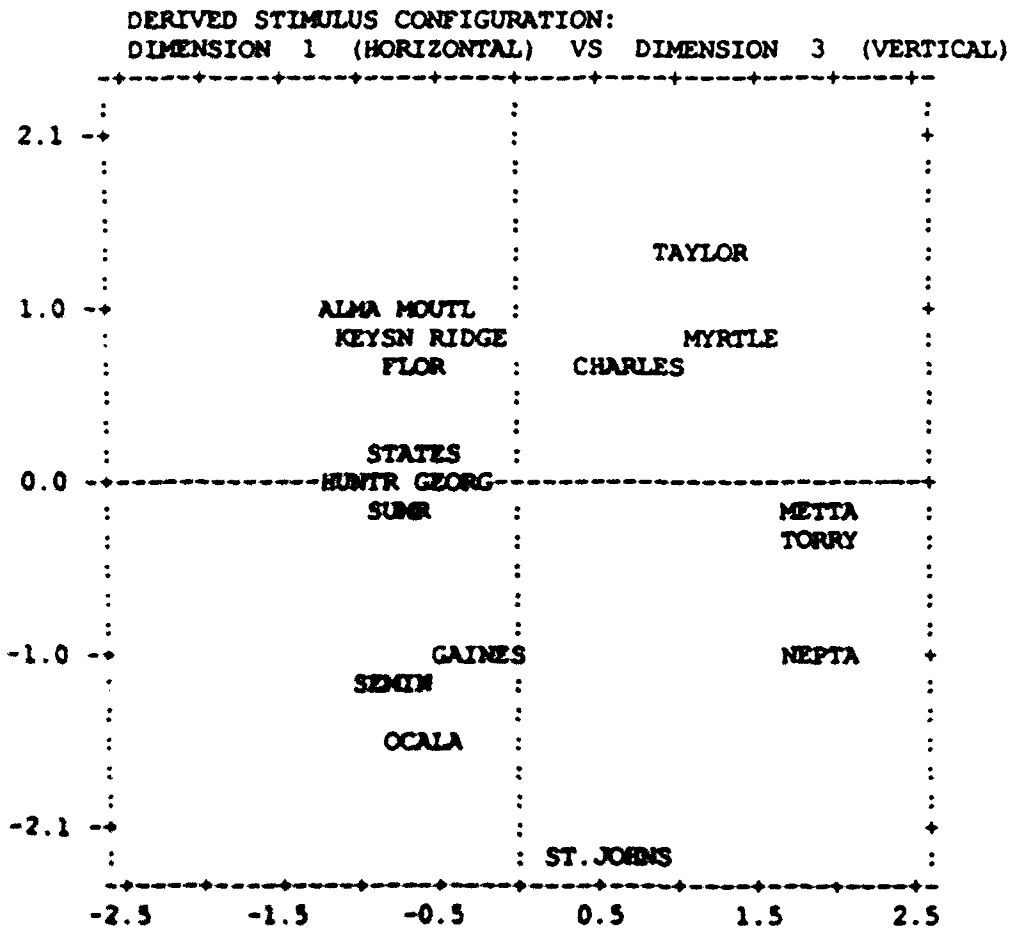

FIGURE B16. TMU DIMENSIONS, ONE VERSUS THREE

DERIVED STIMULUS CONFIGURATION:
DIMENSION 2 (HORIZONTAL) VS DIMENSION 3 (VERTICAL)

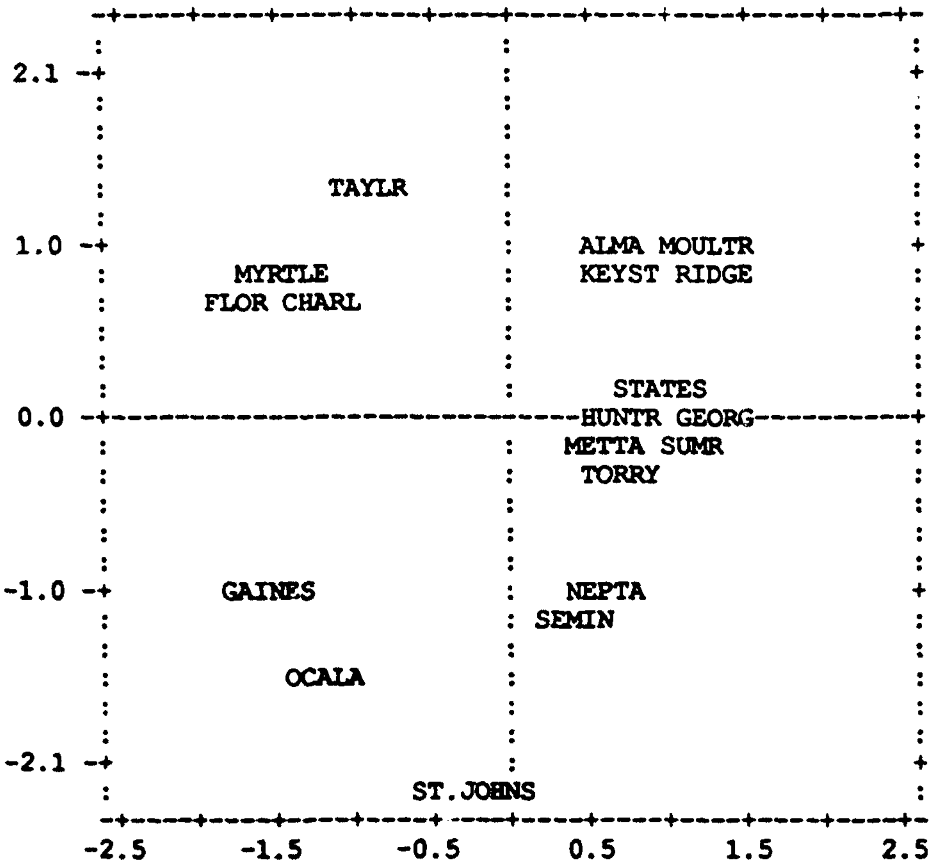

FIGURE B17. TMU DIMENSIONS, TWO VERSUS THREE

DERIVED PARTICIPANT WEIGHTS:
DIMENSION 1 (HORIZONTAL) VS DIMENSION 2 (VERTICAL)

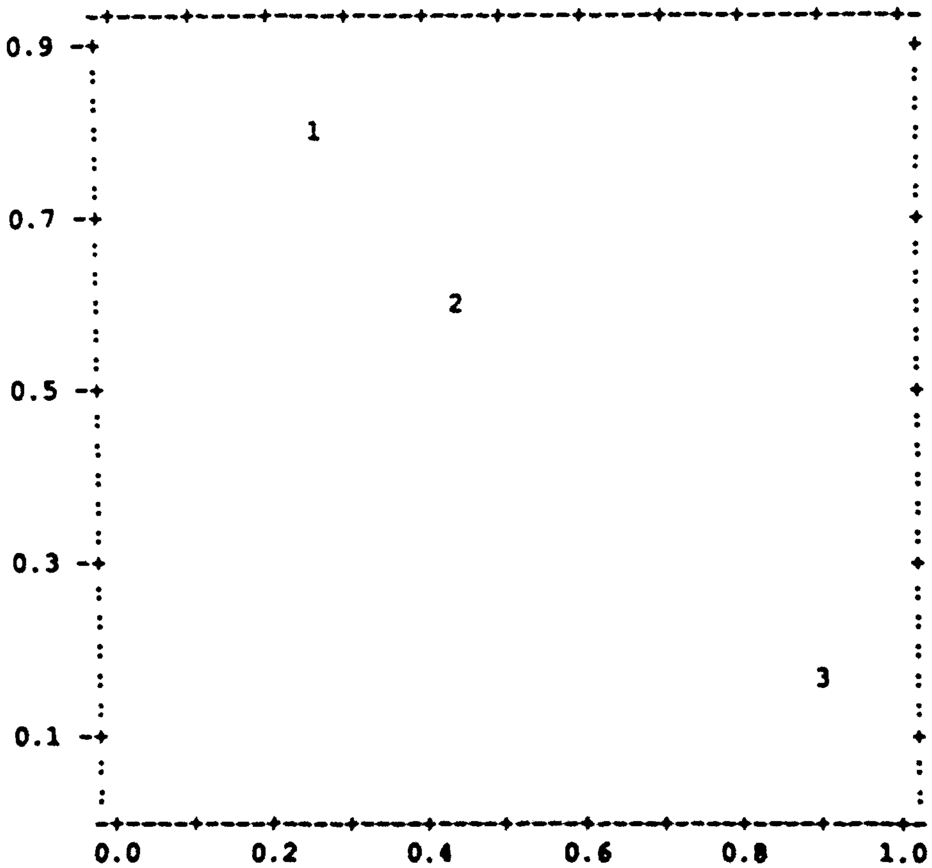

FIGURE B18. PARTICIPANT WEIGHTS FOR TMU STAFF, ONE VERSUS TWO.

DERIVED PARTICIPANT WEIGHTS:
DIMENSION 1 (HORIZONTAL) VS DIMENSION 3 (VERTICAL)

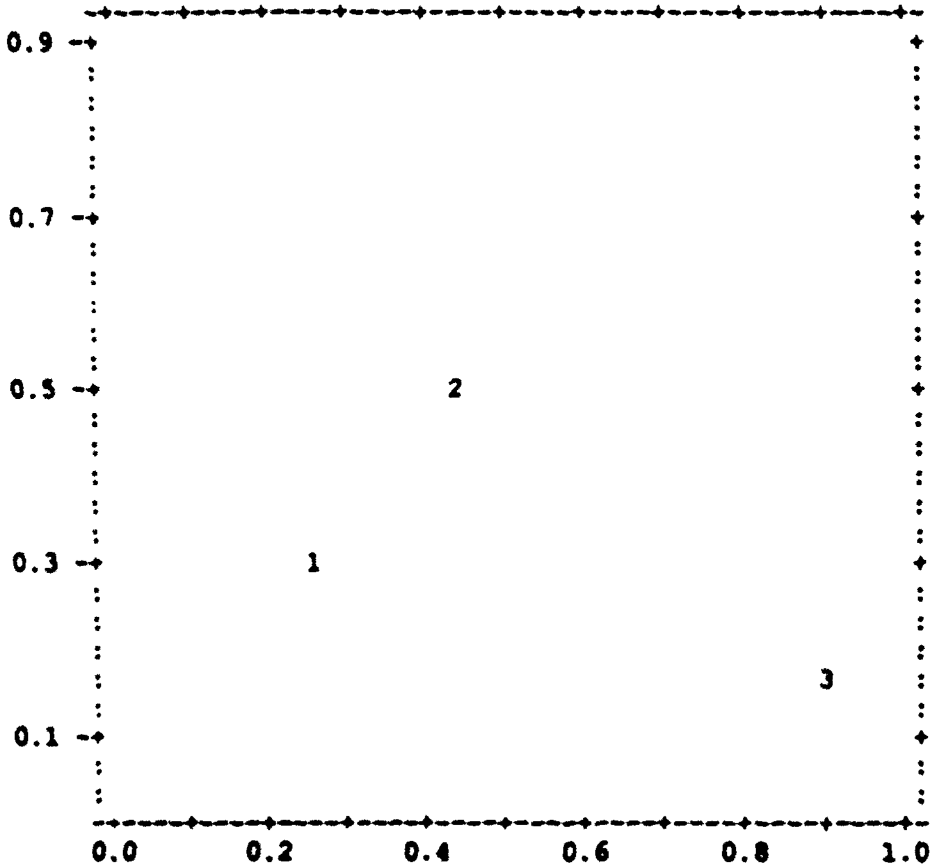

FIGURE B19. PARTICIPANT WEIGHTS FOR TMU STAFF, ONE VERSUS THREE.

DERIVED PARTICIPANT WEIGHTS:
DIMENSION 2 (HORIZONTAL) VS DIMENSION 3 (VERTICAL)

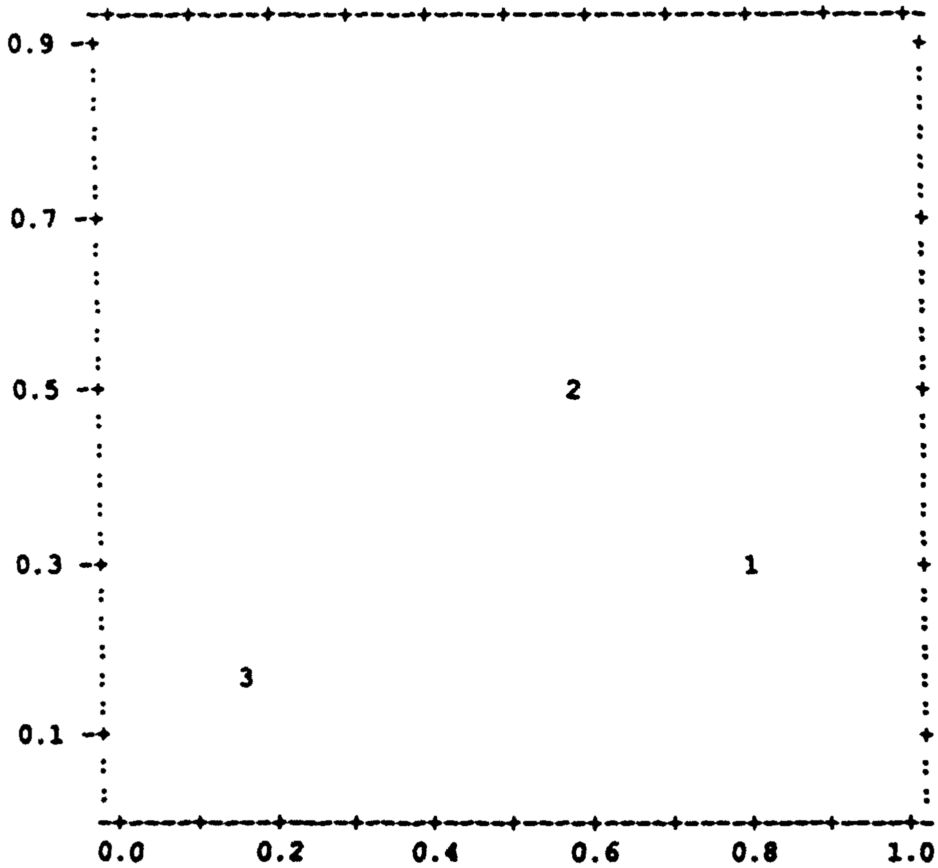

FIGURE B20. PARTICIPANT WEIGHTS FOR TMU STAFF, TWO VERSUS THREE.

In order to locate property vectors, ratings of sectors on the initial complexity factors were regressed over the set of MDS stimulus coordinates for the dimensions for each group (APSs or TMU). Those factors that had significant multiple correlations with the MDS dimensions were assumed partially to explain the configuration of the sectors in the stimulus space. Ratings of all 38 Jacksonville ARTCC sectors on the 24 initial complexity factors were used as dependent variables in an attempt to identify property vectors. In each case, it was possible to fit property vectors that accounted for an acceptable amount of variance, that were statistically significant, and that were correlated with one or more of the dimensions in the stimulus space (Kruskal and Wish, 1988).

Table B1 shows the property vectors for the APSs. The rightmost column shows the regression beta weights and their correspondence with MDS dimensions. The sign of each beta weight indicates the angle of the property vector in the MDS stimulus space.

In each case, for the APS data, more than one property vector was correlated with each dimension (table B1). Given the pattern of correlations, it appeared that the first dimension described sectors with many climbing and descending flights, requiring the application of many different ATC functions or procedure. These sectors also typically contained varying numbers of facilities requiring frequent interfacility coordination. The second dimension was defined primarily by the mix of aircraft types (VFR, IFR, etc.). A third vector in the space was related to the number of departing and arriving aircraft.

Table B2 shows the property vectors for the TMU staff. The pattern of correlations for TMU staff is more complex because the MDS space was three dimensional (table B2). For these data, the first dimension combined number of departure and arrival transitions, radio coverage, and intersecting flight paths, while the second dimension incorporated number of departing and arriving aircraft, mix of aircraft, and number of military requirements. There were no clear correlations with the third MDS dimension, but there were several other property vectors. The first three additional property vectors were not parallel with the primary MDS dimensions. These three property vectors corresponded with weather, airline hubbing, and multiple functions. For the TMU data, a fourth vector combined number of facilities, amount of climbing and descending traffic, and size of airspace.

Table B1. Regression Results for Multidimensional Scaling Solutions for Airspace Procedures Specialists

PROPERTY VECTOR	R^2	SIGN.	DIMENSION BETA WEIGHTS
CLIMBING/DESCENDING FLIGHTS	.95	.0005	1(-.78)
MULTIPLE FUNCTIONS	.94	.0009	1(-.96)
AIRCRAFT MIX	.92	.0019	2(-.87)
NO. OF FACILITIES	.91	.0027	1(-.79)
COORDINATION	.90	.0029	1(-.83)
NO. DEPARTING/ARRIVING AIRCRAFT	.90	.0035	1(-.68) & 2(-.59)

Table B2. Regression Results for Multidimensional Scaling Solutions for Terminal Management Unit Staff

PROPERTY VECTOR	R^2	SIGN.	DIMENSION BETA WEIGHTS
NO. DEPARTING/ARRIVING AIRCRAFT	.70	.0003	2(-.71)
AIRCRAFT MIX	.67	.0007	2(-.80)
AIRLINE HUBBING	.64	.0013	3(-.61) & 2(-.57)
WEATHER	.62	.0018	3(-.58) & 2(.49)
NO. OF FACILITIES	.60	.0026	1(-.54) & 2(-.58)
CLIMBING/DESCENDING FLIGHTS	.59	.0028	1(-.51) & 2(-.59)
STARS & SIDS	.58	.0037	1(-.63)
FREQUENT MILITARY REQUIREMENTS	.57	.0045	2(-.61)
RADAR/RADIO COVERAGE	.54	.0070	1(.73)
INTERSECTING FLIGHT PATHS	.54	.0071	1(-.73)
MULTIPLE FUNCTIONS	.54	.0072	1(-.50) & 3(-.47)
SIZE OF AIRSPACE	.52	.0094	1(.53) & 2(.53)

APPENDIX C

WORD SHAPE SORTING TEST (WSST) RESULTS

WSST scores for the FPLs, APSs, and TMU personnel ranged from 6 to 59 (shown in table C1). Across these groups, 31 percent of participants scored 20 or below (indicating a verbal/analytic problem solving style); 47 percent fell between 20 and 40 (showing no strong preference); and 22 percent scored above 40 (indicating a spatial/global style).

The WSST scores for different specialization areas were averaged to obtain a mean (M) for each group. A test of the group means using Analysis of Variance (ANOVA) did not indicate significant differences between North ($M = 33.4$), South ($M = 31.2$), East ($M = 31.4$), West ($M = 32.8$), Central ($M = 27.0$), Developmentals ($M = 33.6$), and Airspace Procedures/TMU staff ($M = 29.33$), $F(6, 29) = 0.96$, $p = .996$. The mean times required to complete the WSST also did not vary between specialization areas. The results (in seconds) were: North ($M = 236.2$), South ($M = 436.4$, East ($M = 219.2$), West ($M = 355.0$), Central ($M = 291.0$), Developmentals ($M = 187.6$), and Airspace Procedures/TMU staff ($M = 279.2$), $F(6, 29) = 1.07$, $p = .402$.

Product-moment correlations were calculated between WSST scores, INDSCAL weirdness values[1], and collapsed MDS participant weights for the FPLs in the main study. The purpose of this analysis was to determine whether or not thinking style accounted for differences in emphasis on the common stimulus space dimensions, as reflected by weirdness values and collapsed INDSCAL weights. No significant correlations were found between the WSST score and either weirdness or weight space values. (The correlation of the WSST score with weirdness was -0.20. The WSST score and collapsed weight correlation was 0.20.)

1 A measure of how close a subject's MDS scores came to the others in the group or shared stimulus space.

Table C1. Word-Shape Sorting Test Scores for FPL, APS, and TMU Participants

4	CENTRAL	FPL	365	26
5	CENTRAL	FPL	172	10
6	EAST	FPL	272	39
7	EAST	FPL	205	7
8	EAST	FPL	201	39
9	EAST	FPL	187	54
10	EAST	FPL	231	18
11	EAST	DEVEL.		34
12	EAST	DEVEL.	203	31
13	EAST	DEVEL.	259	42
14	EAST	DEVEL.	314	25
15	EAST	DEVEL.	162	36
16	NORTH	FPL	177	39
17	NORTH	FPL	256	12
18	NORTH	FPL	173	59
19	NORTH	FPL	225	19
20	NORTH	FPL	350	38
21	SOUTH	FPL	298	36
22	SOUTH	FPL	1221	40
23	SOUTH	FPL	217	9
24	SOUTH	FPL	211	58
25	SOUTH	FPL	235	13
26	WEST	FPL	461	24
27	WEST	FPL	428	26
28	WEST	FPL	311	36
29	WEST	FPL	221	28
30	WEST	FPL	354	50
APS 1	N/A	TMU	287	20
APS 2	N/A	TMU	307	8
APS 3	N/A	TMU	479	31
TMU 1	N/A	APS	176	50
TMU 2	N/A	APS	218	58
TMU 3	N/A	APS	208	9

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